REPORT No. 386

MANEUVERABILITY INVESTIGATION OF AN F6C-4 FIGHTING AIRPLANE

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SUMMARY

In order to compare the relative maneuverability of two fighting airplanes and to accumulate additional data to assist in establishing a satisfactory criterion for the maneuverability of any airplane, the National Advisory Committee for Aeronautics, at the request of the Bureau of Aeronautics, Navy Department, has conducted maneuverability investigations on the F6C-3 (water-cooled engine) and the F6C-4 (air-cooled engine) airplanes. The investigation made on the F6C-3 airplane has been previously reported. This report contains the results of the investigation made on the F6C-4 airplane.

Measurements of air speed, angular velocity, linear acceleration, temperature, pressure, and the position of the controls were made for practically all the kinds of military maneuvers required of this type of airplane. Flight path coordinates were secured for most of the maneuvers by means of a special camera obscura developed for this investigation. The results are given in the form of curves, some showing the variation of the measured quantities with respect to time, others, the variation of some maximum quantities with respect to air speed. In addition, all maximum quantities are tabulated.

A comparison of the results with those obtained in the investigation conducted on the F6C-3 airplane shows that: With practically the same speed and control movement, the F6C-4 completed a loop in 10 per cent less time than did the F6C-3; in dives the F6C-3 increased its speed more rapidly than did the F6C-4; and the minimum radius of turn was found to be 135 feet at 61.5 miles per hour for the F6C-4, and 155 feet at 76 miles per hour for the F6C-3.

INTRODUCTION

At the request of the Bureau of Aeronautics, Navy Department, the National Advisory Committee for Aeronautics at Langley Field, Va., is conducting a series of maneuverability investigations on a number of military airplanes. Data have been previously reported on tests made on an F6C-3 airplane. (Reference 1.) Similar data, but of a broader nature, are given herein for an F6C-4 airplane. As stated in the above reference, the purpose of these tests is the establishment of certain quantitative data which it is hoped will facilitate the rating of military airplanes in regard to maneuverability.

Instruments in the airplane were used to record linear accelerations along the three reference axes, angular velocities about these axes, the air speed, and the position of the control surfaces throughout practically all types of military maneuvers. A camera obscura, which was developed for this investigation, stationed on the ground was employed to obtain flight paths for a number of the maneuvers. The results are given in the form of curves, some showing the variations of measured quantities with respect to time, others, the variation of some maximum quantities with respect to air speed. A comparison with the results obtained in the F6C-3 investigation is made wherever this is possible.

APPARATUS AND METHODS

APPARATUS

The airplane employed in the present investigation was an F6C-4 Curtiss Fighter, powered with an air-cooled Pratt and Whitney R-1300 engine. It weighed about 350 pounds less than the F6C-3 airplane which is powered with a Curtiss D-12 water-cooled engine. In all other important respects the two airplanes were identical. The Navy's principal specifications for the F6C-4 are presented in the appendix. The airplane as used in this investigation weighed about 2,574 pounds and had its *c. g.* 5.7 inches ahead of the leading edge of the lower wing.

Recording-instrument installation.—The instruments installed in the airplane during this investigation were of the standard N. A. C. A. photographically-recording type. They consisted of the following: A control-position recorder (Reference 2) for giving the control movement during a maneuver; three angular-velocity recorders (Reference 3) for recording angular velocities about the three reference axes of the airplane; a 3-component accelerometer (Reference 4) for recording the linear accelerations along the three reference axes; a recording tachometer used primarily for giving engine speeds in spins; and a timer for synchronizing the instrument records. A performance recorder containing an air-speed unit (Reference 5), temperature unit, and an aneroid unit was also employed to determine air speed, altitude, and air density.

The above instruments, with the exception of the control-position recorder, which was located in the cockpit, were placed in the main gasoline tank bay of the fuselage. This necessitated the use of the 22-gallon underslung tank shown in the general view of the F6C-4 airplane. (Figure 1.)

Radio equipment.—One-way radio telephone communication from the ground to the airplane was used to coordinate flight and ground operations. The microphone employed in the transmitting system was located just outside the camera obscura. A radio receiver, designated as type SRA-3 by the Signal Corps, United States Army, was installed in the airplane. This receiver was operated from an antenna extending from the landing gear struts to the tail-skid section of the fuselage. The high-tension circuit of the engine was shielded to reduce engine ignition interference.

Camera obscura and accessories.—The camera obscura was designed to perform two functions: First, to determine rapidly the wind speed and direction at the altitudes of the maneuver to be performed; and second, to record the flight path of the airplane during the maneuver. It is illustrated in Figures 2 and 3. Actually, it is a large camera, approximately 7 feet square by 7 feet high, so mounted on a concrete base that it may be rotated into alignment with the wind. A circular scale in 5° divisions from the magnetic north is painted on the base. The lens employed may be mounted in the side (as illustrated) to record maneuvers performed in a vertical plane, or in the roof to record those in a horizontal plane. The records (fig. 4) are made on a 30-inch by 30-inch film, the required exposure and time between exposures being obtained by use of a special focal plane shutter. (Reference 6.) The film is supported at the proper distance from the lens on a table whose top can be quickly rotated from the inclined position shown to a horizontal position. In addition, this table can be lowered enough to allow the protractor sheet support, used during wind measurements, to be placed in the focal plane of the lens.

The wind measurements were recorded by other than photographic means. This necessitated the following accessories: A combination perpendicular bisector and dividers, sheets of paper with a protractor scale, and a sight placed outside the camera obscura. The electric pencil (fig. 5) is used by an operator inside the camera to follow the airplane image on the wind screen during wind runs. It is operated by an electromagnet in series with a timer. The timer completes a circuit at one-half second intervals, producing jogs in the line, as shown in Figure 6. Ground-speed vectors and necessary perpendicular bisectors may be quickly drawn with the combination perpendicular bisector and dividers shown in Figure 5. The protractor sheets (fig. 6), on which the wind run paths were recorded, are about 30 inches square and have a 20-inch circle with 1° divisions.

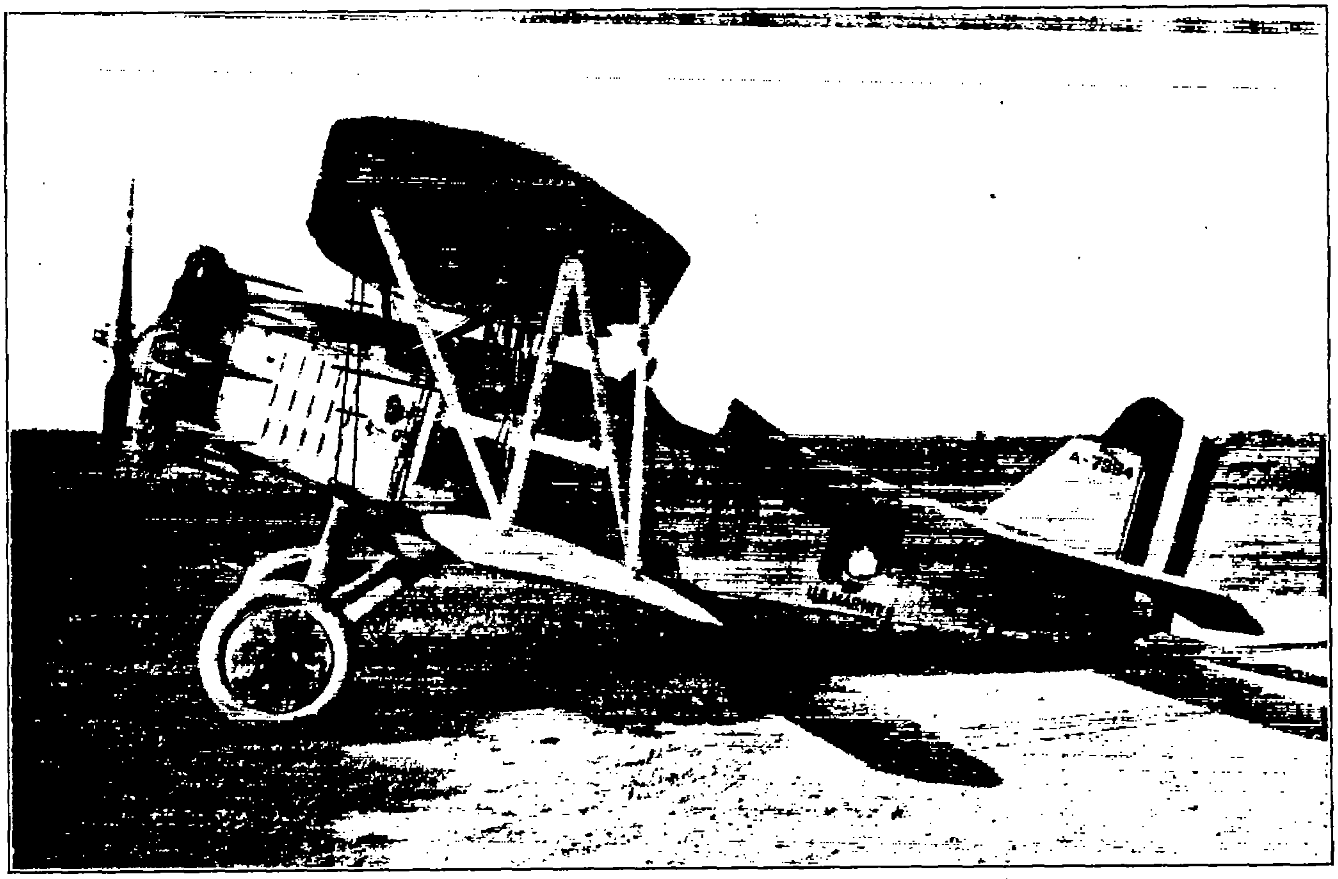

FIGURE 1.—F6C-4 airplane

The ground observer's sight for aligning maneuvers with the film screen is shown attached to the side of the camera obscura in Figure 2. This sight consists of a frame with two sets of three wires at right angles and a sighting bead about six inches in the rear of the plane of the frame. The intersection of the center wires corresponds to the center of the camera field, while the two outer wires of each set outline the field of the camera.

METHOD OF TESTS

The following maneuvers were included in the flight program of this investigation:

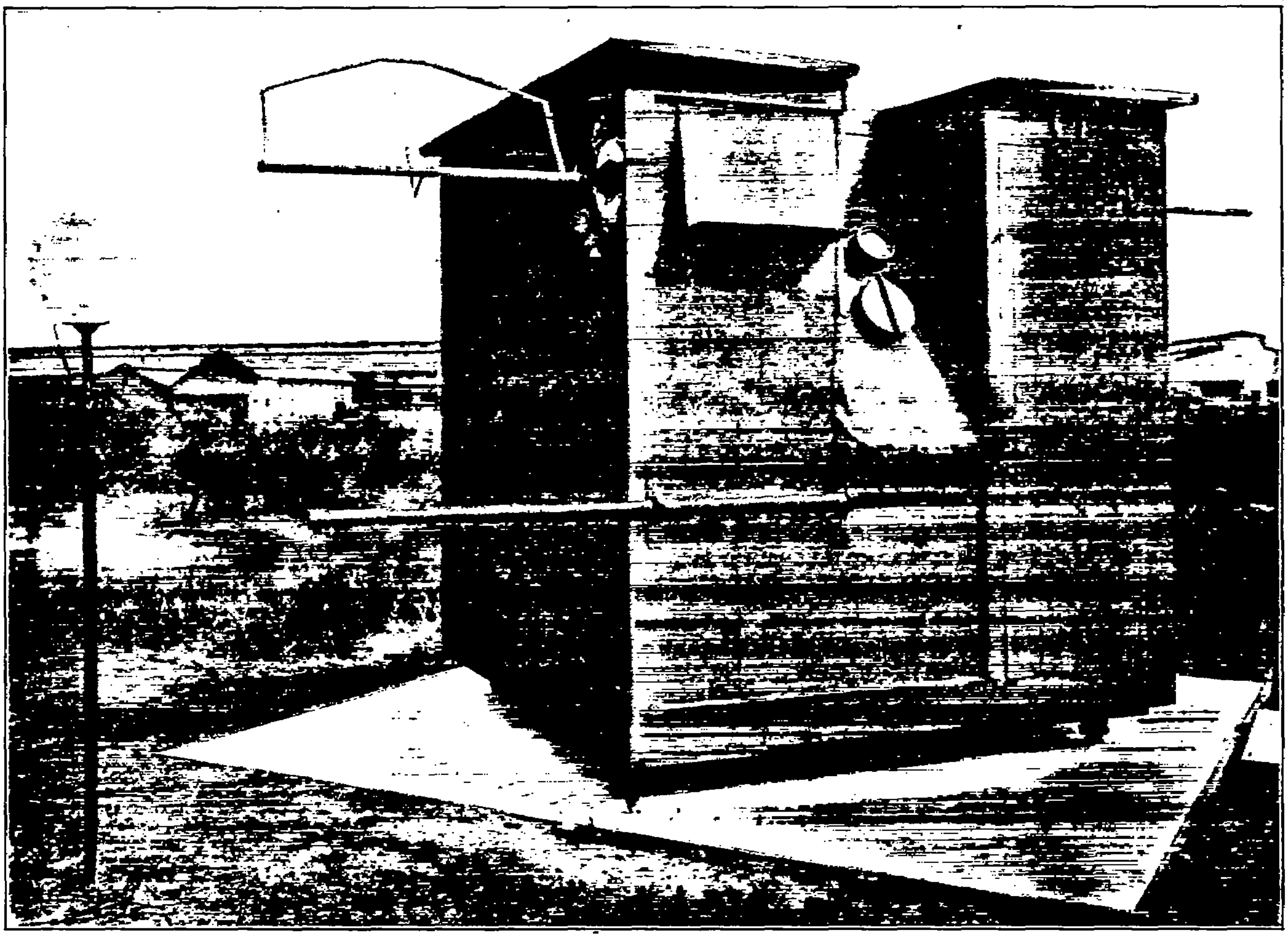

FIGURE 2.—Camera obscura

Loops.
Push-downs.
Pull-outs from dives.
Pull-ups from horizontal flight.
Turns of 180° in vertical and horizontal planes.
Aileron maneuvers.
Rudder maneuvers.
Turns for the determination of minimum radius of turn.
Power-on and power-off spins.
Barrel rolls.

Before performing each maneuver wind runs were made to find the direction and speed of the wind at the altitude or altitudes at which the maneuver was to be made. This information was required to correct the flight path measured with the camera obscura to true flight path; i. e., path through the air. This correction can be made more readily and with greater accuracy if the maneuver is started directly into or with the wind, so the first consideration in the wind runs was the determination of the wind direction to establish the course to be flown in the maneuver.

The procedure used in determining the wind direction was as follows: The airplane was flown at a constant air speed across the camera obscura in three different directions, approximately 120° apart. A projection of the track of the airplane was obtained during each run on the protractor sheet in the camera obscura by following the image of the airplane with the electric pencil (fig. 6). Vectors, proportional to the ground speeds, were obtained directly from the lengths of the tracks between a definite number of the jogs produced by the electric pencil. These vectors were laid off from a common center, and a circle was passed through their ends. The line drawn from the intersection of the vectors to the center of the circle established the wind direction. Also, during each wind run, records were made in the airplane of air speed, barometric pressure, and temperature. These were made to determine the true air speed used subsequently to compute the magnitude of the wind velocity.

The course to be flown, as determined from the wind direction, was then radioed to the pilot, and while he was adjusting his course, the camera obscura was rotated into position and prepared for photographic recording.

A ground observer, using the sight on the side of the camera obscura, directed the pilot by radio in such a manner as to bring the airplane into the proper part of the field of the camera obscura. While following these directions, the pilot continually adjusted his course to that previously given him. When the airplane actually entered the field of the camera, the camera shutter and the instruments in the airplane were started simultaneously on receipt of orders from the ground observer, and approximately one second later, the maneuver was started. In each maneuver, except the turns for the determination of minimum radius of turn, measurements were made of the flight path, air speed, angular velocity, linear accelerations, position of the control surfaces, temperature, and barometric pressure.

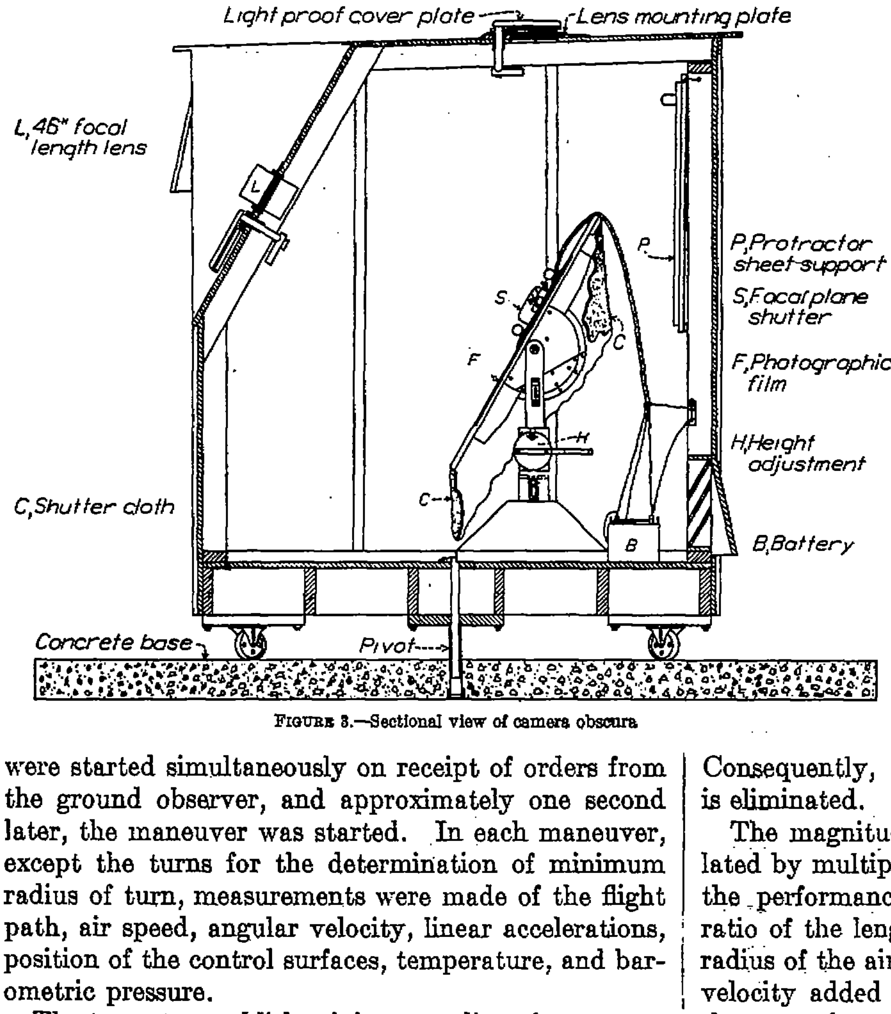

FIGURE 3.—Sectional view of camera obscura

The turns to establish minimum radius of turn were made without the use of the camera obscura. In these tests the pilot put the airplane into a turn with full throttle setting, gradually tightened up the turn without changing the throttle, and finally took records after the airplane had reached what he believed to be the tightest steady turn possible at a predetermined air speed. This procedure was repeated for a number of different air speeds.

COMPUTATION OF RESULTS

Control-position, angular-velocity, and linear-acceleration curves are obtained directly from the instrument records. The aileron positions are given for the left aileron, which moves with respect to the right as shown in Figure 7. Angular accelerations and displacements are found from the recorded angular velocities by graphical differentiation and mechanical integration, respectively. Resultant angular velocity is found by adding the roll, pitch, and yaw components vectorially. Curves of true air speed are obtained either from air-speed or camera-obscura records. The density factor necessary for the conversion of indicated to true air speed is calculated from the recorded temperature and pressure. The recorded air speed is subject to an interference correction, the magnitude of which is known only for unaccelerated flight. The accuracy of the recorded air speed is therefore questionable in maneuvers, and for that reason the airspeed in accelerated flight is obtained from the camera obscura records whenever possible.

When recording maneuvers made in a vertical plane, the axis of the camera lens is at an angle of 60° from the vertical, and the recorded flight paths are, therefore, in error because of perspective. To eliminate this error a perspective grid was constructed in accordance with the foreshortening that would be obtained by photographing uniformly spaced vertical and horizontal lines with the camera axis 60° to the vertical. The perspective grid is placed under the film record, and the coordinates of the images with respect to it are read. Consequently, the distortion caused by perspective is eliminated.

The magnitude of the wind velocity is next calculated by multiplying the true air speed obtained from the performance recorder during wind runs by the ratio of the length of the wind-velocity vector to the radius of the air-speed circle. (See fig. 5.) The wind velocity added algebraically to the true air speed at the start of a maneuver gives the ground speed, which, with the rate of exposures, determines the scale of the path. The correction for wind for each image is obtained by multiplying the magnitude of the wind velocity by the time from the start of the maneuver divided by the scale factor.

Air speed is computed from the corrected path by measuring the displacement between the images and dividing this by the time between exposures. The angle of attack is found by measuring the angle between the X axis of the image and the tangent to the corrected flight path at any given point.

PRECISION OF RESULTS

Frequent instrument calibrations were made so that errors due to change of calibration were practically eliminated. The records were legible enough to permit measuring them to the nearest 0.01 inch, so that, with the sensitivities used during this investigation, linear accelerations are accurate to ± 0.05 g, and control surface angles, to $\pm \frac{1}{4}$ of a degree. The recorded air-speed error is in the neighborhood of 2 per cent for unaccelerated flight, and is unknown in accelerated flight. The error in the air speed secured from the camera-obscura path, however, is probably within 5 per cent for all conditions of flight. The slight time lag in the angular-velocity recorders during the periods of high angular acceleration has not been eliminated. Consequently, peak values are probably about 2 per cent low.

In computing the error present in the flight paths obtained from the camera obscura, three possible errors were considered: First, the airplane was not on the proper course; second, the wind velocity was in error; and, third, the scale was in error. A study of some of the results indicated that the course might be in error as much as 6°. The error in the wind direction was within $\pm 5°$ and the error in the magnitude was found to be as much as 3.5 miles per hour. The error in scale based upon the average of the scales derived from the image size and the ground speeds at the start of the maneuvers was found to be slightly less than 2 per cent. Since the cosine of the error in the course and the cosine of the error in the wind direction are practically unity, these errors are negligible. The average speed during the maneuvers was 130 miles per hour, and the resulting error caused by wind was, therefore, slightly over 2 per cent. On the whole, the probable error in the flight paths is, therefore, about ± 4 per cent for the abscissae and ± 2 per cent for the ordinates.

The probable error in synchronization between the instrument records and the camera-obscura records is only a fraction of a second, and may be attributed to the differences in the speed of human reactions. This error, though small, has a considerable effect on the angle of attack measurement. The individual values of angle of attack may be scaled from the camera-obscura film with small error, but owing to the high rate of change of angle of attack, a small error in synchronization may result in an angle, for a given speed and normal acceleration, which is 25 per cent or more in error.

RESULTS

The results of this investigation are presented chiefly in the form of time-history curves and flight-path graphs. Time intervals in agreement with those of

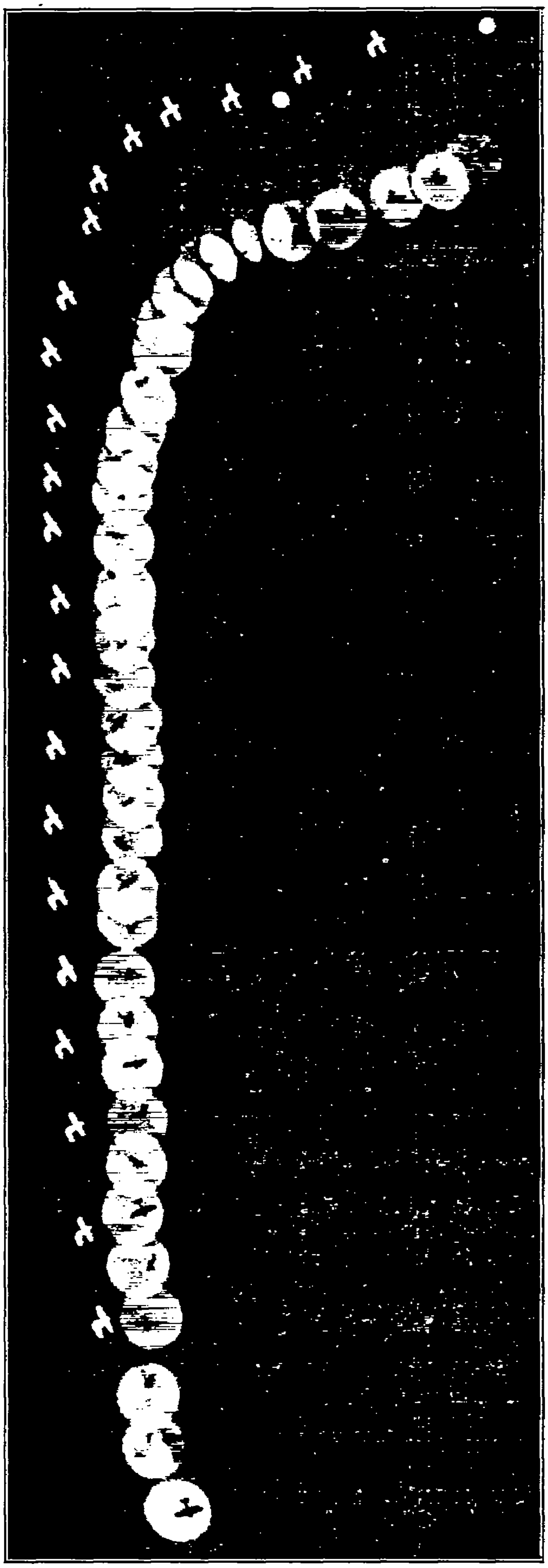

FIGURE 4.—Camera obscura record of spin

time-history curves are given on the flight-path graphs. Some of the results are compared with those obtained on the F6C–3 airplane. The maneuvers are presented in the following order:

Loops, Figures 8 and 9.
Push-downs, Figure 10.
Pull-outs from dives, Figures 11, 12, and 13.
Pull-ups from horizontal flight, Figures 14, 15, 16, and 17.
Half loop half roll, Figure 18.
Half roll half loop, Figure 19.
180° vertically banked turns, Figures 20, 21, 22, and 23.
Abrupt wing-over turn, Figure 24.
Aileron maneuvers, Figures 25 and 26.
Rudder maneuvers, Figures 27 and 28.

	F6C–3 normal loop	F6C–4 normal loop	F6C–4 tight loop
Air speed at start of loop (m. p. h.)	150	152	147
Maximum angular velocity (rad./sec.)	.79	.80	1.00
Maximum normal acceleration in pull-up at start of loop (g)	2.90	3.60	5.00
Normal acceleration at top of loop (g)	1.00	1.40	1.80
Maximum normal acceleration in coming out of loop (g)	3.75	4.00	3.10
Maximum angle of attack (degrees)	22	23	24
Height of loop (ft.)	560	465	370
Gain of altitude at end of loop (ft.)	50	100	20
Time to complete loop (sec.)	13.5	12.0	10.0

The maximum angular velocities for the three loops were recorded near the tops of the loops, while the maximum angle of attack occurred just before the top. The maximum normal acceleration was recorded in coming out of the two normal loops, while in the tight loop the maximum value was obtained at the start.

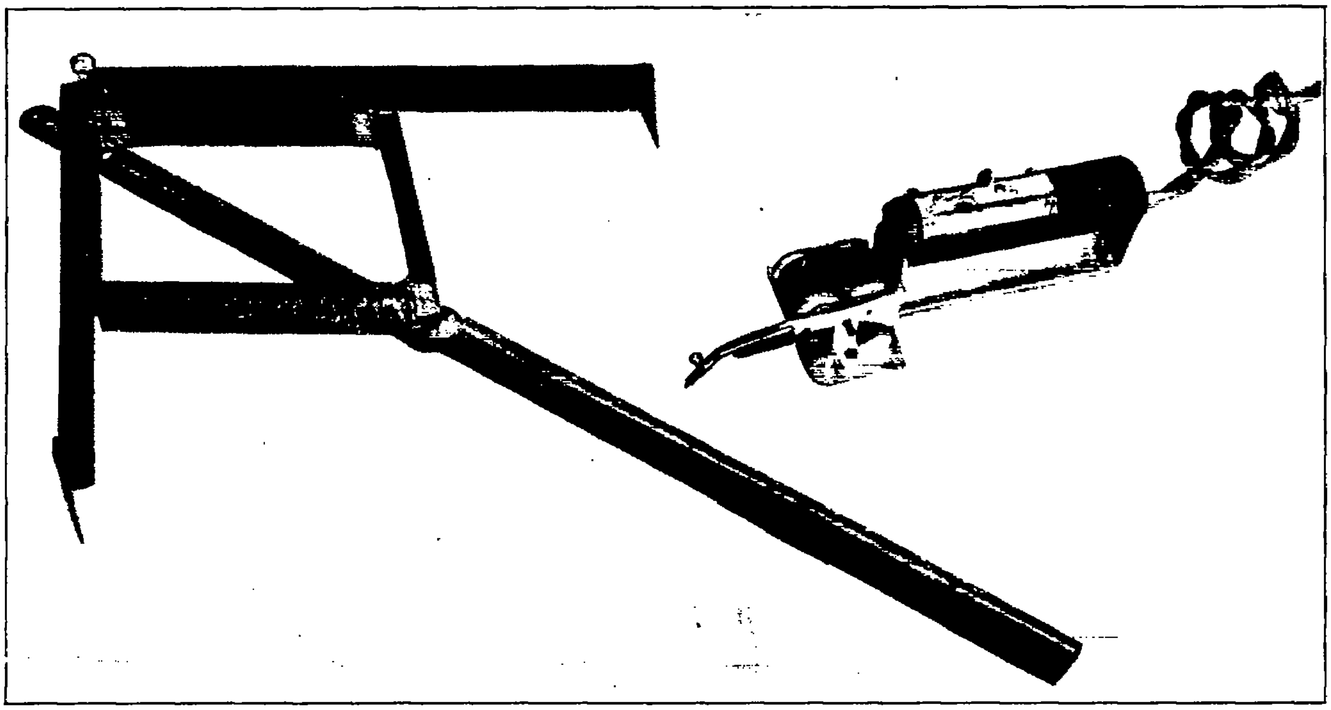

FIGURE 5.—Electric pencil and proportional dividers

Turns of minimum radius, Figure 29.
Spins, Figures 30, 31, 32, and 33.
Barrel rolls, Figure 34.

Loops.—Two loops were executed from an air speed of approximately 150 miles per hour. The first was a normal loop and is comparable to the high-speed loop in the F6C–3 maneuverability report (Reference 1), since the control movement and starting air speed were about the same for the two maneuvers. The second loop will be designated a tight loop because of the comparatively abrupt control action and the large elevator displacement which was more than twice that recorded on the normal loop.

The principal data for the three loops are given in the table below, while the time histories for the F6C–4 loops are shown in Figures 8 and 9.

A comparison of the data for the two normal loops indicates that the F6C–4 is a more maneuverable airplane as shown by the higher linear acceleration and smaller over-all flight-path dimensions together with about 10 per cent shorter time required to complete the maneuver.

Push-downs.—The time histories for three abrupt push-downs are presented in Figure 10. Although these maneuvers were made at air speeds of 85, 100, and 130 miles per hour, the maximum normal accelerations are practically the same. This is no doubt caused by the difference in the control movement which was probably governed by the disagreeable sensation of this type of maneuver. It may be noted that as the starting speed of the push-down is increased the maximum angular velocity attained in the maneuver is decreased, while the maximum angular acceleration is increased. The maximum negative angle of attack decreases as the starting speed increases. This would be expected with equal normal accelerations. With the initial air speeds of 85, 100, and 130 miles per hour, the altitude losses in the first three seconds of each maneuver were 140 ft, 170 ft, and 175 feet, respectively. With an initial air speed of 100 miles per hour the altitude loss in four seconds was 290 feet with the F6C-4 as compared with 405 feet for the F6C-3. This is undoubtedly due to the greater weight/drag ratio of the F6C-3.

Pull-outs from dives.—Three pull-outs from dives were executed at different speeds primarily to determine the loss of altitude during recovery with abrupt control action. The time histories with the respective paths are shown in Figures 11, 12, and 13. The principal quantities are presented in the table below with those of the F6C-3 maneuver that are most comparable.

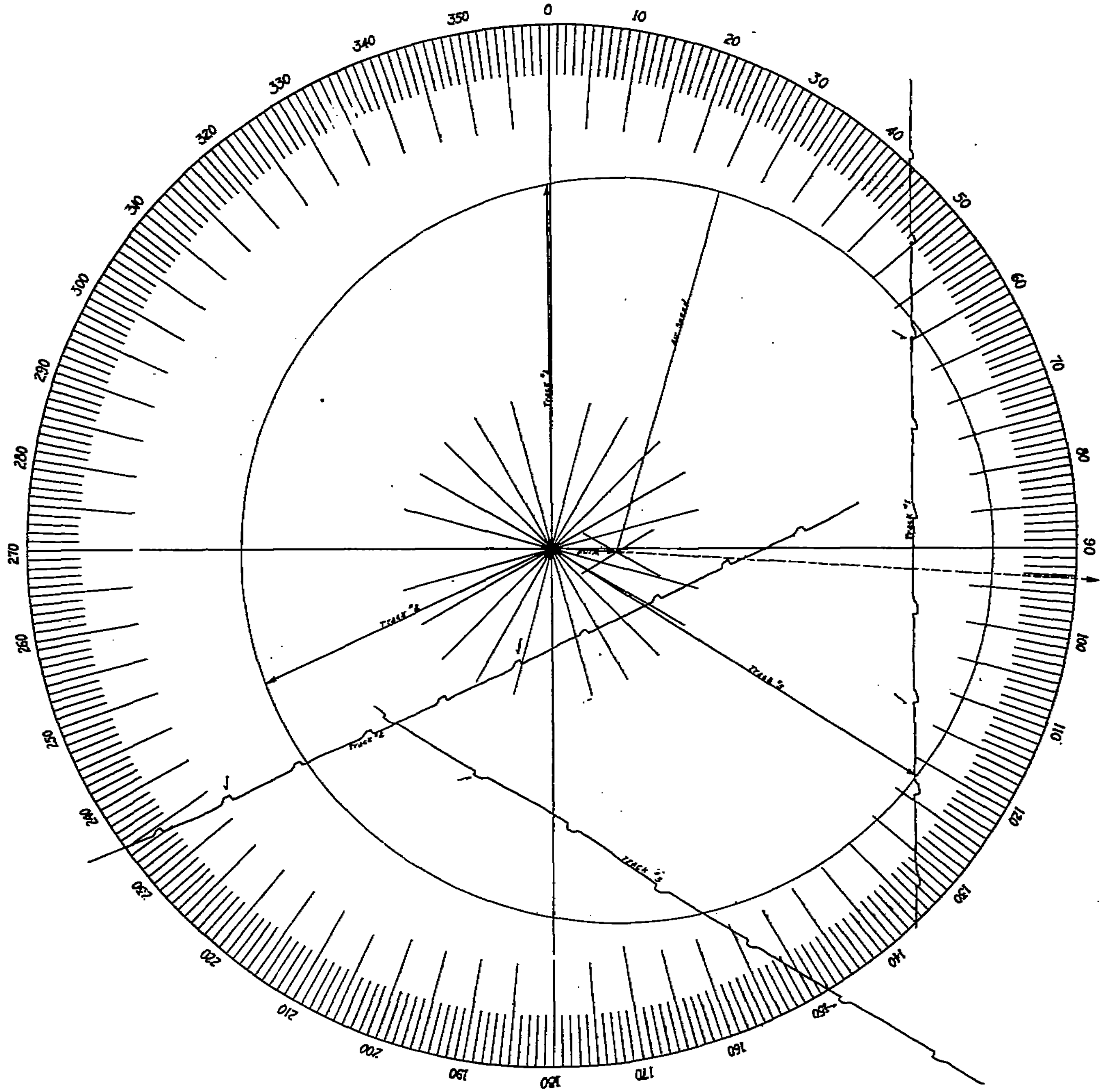

FIGURE 6.—Protractor sheet illustrating method of determining wind

	F6C-4	F6C-4	F6C-4	F6C-3
Speed at start of pull-out (m. p. h.)	130	140	175	140
Maximum elevator displacement (degrees)	35.5	34.5	31.0	27.0
Time to reach above displacement (sec.)	1	1	0.8	1.4
Maximum angular acceleration (rad./sec.²)	3.3	5.8	7.0	4.8
Maximum angular velocity (rad./sec.)	1.64	2.28	2.00	1.45
Maximum normal acceleration (g)	6.4	7.6	9.3	6.6
Maximum angle of attack (degrees)	38	28	25	21
Angle of dive with horizontal (degrees)	70	72	82	70
Altitude lost (ft.)	290	175	340	310

Although the control movement for the first F6C–4 pull-out was more abrupt than for the second, a greater loss of altitude was experienced during the former. This was undoubtedly due to the fact that in the first maneuver the airplane passed well through the burble angle (maximum angle of attack 38°). This caused a large reduction in the lift which resulted in a greater loss of altitude than that found for the second maneuver made at a higher air speed. The data included from the F6C–3 investigation are not strictly comparable with the second F6C–4 pull-out because the control movement of the F6C–3 was less abrupt.

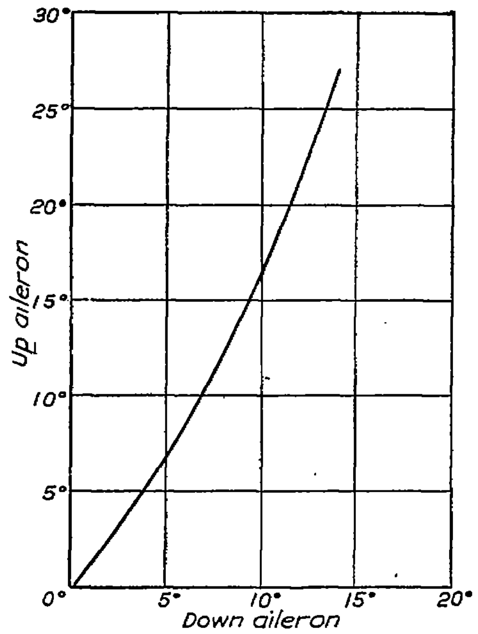

FIGURE 7.—Differential aileron action on F6C–4 airplane

Pull-ups from horizontal flight.—Abrupt, medium, and mild control pull-ups from horizontal flight were executed from speeds of about 80, 125, and 150 miles per hour. In the mild pull-ups the control movements were not alike for the maneuvers at different air speeds, and consequently the results of these pull-ups can not be directly compared. The same is true for the medium pull-ups. For the abrupt pull-ups, however, the control movements were practically the same for all speeds, and, therefore, the results of the different abrupt maneuvers are comparable. Figures 14, 15, and 16 show the time histories for these pull-ups, while the interesting characteristics of the abrupt maneuvers are shown in the table below:

Starting speed (m. p. h.)	80	127	150
Maximum elevator displacement (degrees)	34	35	33.5
Time for above displacement (sec.)	1.25	1.05	1.10
Maximum angular acceleration (rad./sec.^{2})	2.7	3.35	3.90
Maximum angular velocity (rad./sec.)	.99	1.58	1.66
Maximum longitudinal acceleration (g)	.6	1.4	2.8
Maximum normal acceleration (g)	2.9	6.2	7.8
Angular displacement (degrees)	45	45	45
Time for above displacement (sec.)	1.5	1.1	.95

Examination of the paths shows that the altitude gained in a given time is dependent on the abruptness of control action. In order to facilitate the determination of the effect of speed on abrupt pull-ups, the normal acceleration, angular velocities and times for 30° angular displacement are plotted versus the corresponding indicated air speeds in Figure 17.

Half loop—half roll.—This maneuver (fig. 18) is started with a half loop from level flight and completed by executing a half roll to return to level flight in the opposite direction. The elevator was pulled up gradually to 5° and held there until the airplane was nearly in a vertical attitude, then gradually decreased until a half loop was completed. A small amount of aileron and rudder control was used before the maximum altitude gain of about 655 feet was reached. A half roll was then executed to return to normal flight. The reversal of direction was accomplished in approximately 8 seconds but the roll was not finished until nearly 3 seconds later. The air speed at the start was 145 miles per hour and dropped to 67 miles per hour near the top of the half loop. At the end of the maneuver the flight path was inclined downward.

The interesting quantities are presented in the table below:

Air speed at start (m. p. h.)	145
Minimum air speed (m. p. h.)	67
Maximum elevator displacement (degrees)	9
Maximum rudder (right) (degrees)	23
Maximum aileron displacement (degrees)	13
Maximum angular velocity pitch (rad./sec.)	0.5
Maximum angular velocity roll (rad./sec.)	0.7
Maximum angular velocity yaw (rad./sec.)	0.2
Maximum angular acceleration pitch (rad./sec.^{2})	+0.3 and −0.3
Maximum angular acceleration roll (rad./sec.^{2})	−0.4
Maximum angular acceleration yaw (rad./sec.^{2})	+0.15
Maximum normal acceleration (g)	3.35
Maximum longitudinal acceleration (g)	0.5
Maximum transverse acceleration (g)	0.25
Maximum horizontal displacement (ft.)	575
Gain in altitude (ft.)	655
Time required for a 180° change in direction (sec.)	8

This maneuver, which was developed during the late war, is known as the Immelman turn. A turn of this kind accomplishes a rapid reversal of direction and a gain in altitude at the same time. The time required for a reversal of direction would depend upon the tightness of the half loop, but less altitude would be gained in a more abrupt maneuver.

Half roll—half loop.—This maneuver (fig. 18) consists of a half roll from level flight to an inverted position and then approximately a half loop to return again to level flight in the opposite direction. The half roll was executed by means of the ailerons alone, and the half loop was performed by starting the elevator movement just before the half roll was completed. No attempt was made to remain in horizontal flight during the roll and, as a result, the flight path shows considerable gain in altitude before the half loop was started. From the start of the half loop, the airplane veered off to the left with respect to the original direc-

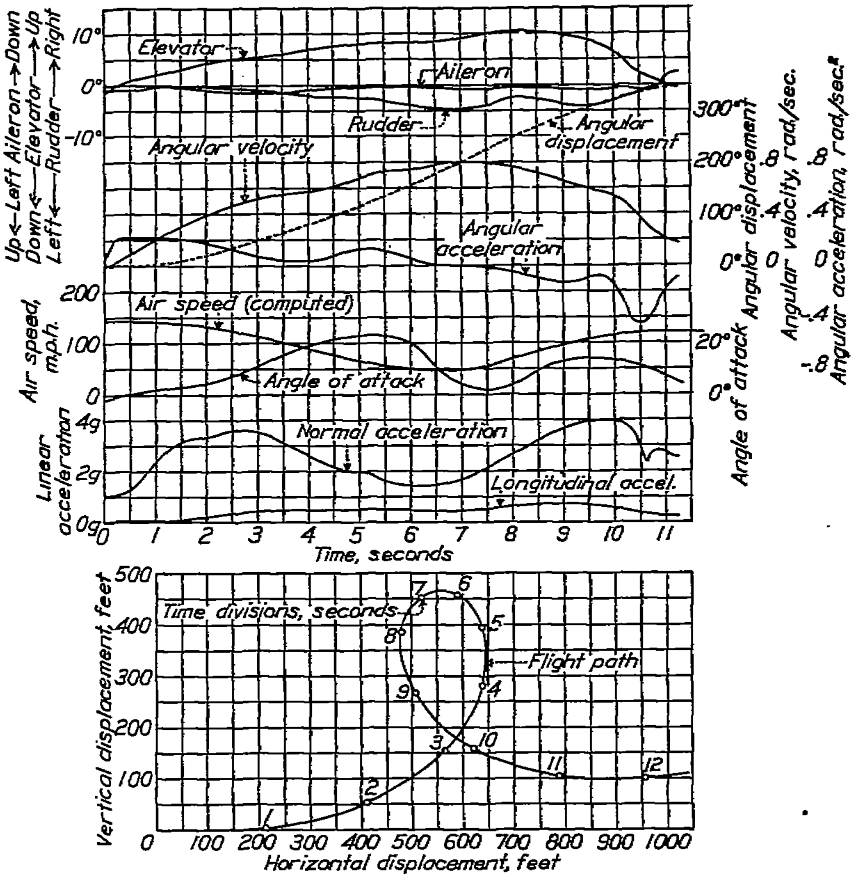

FIGURE 8.—Normal loop

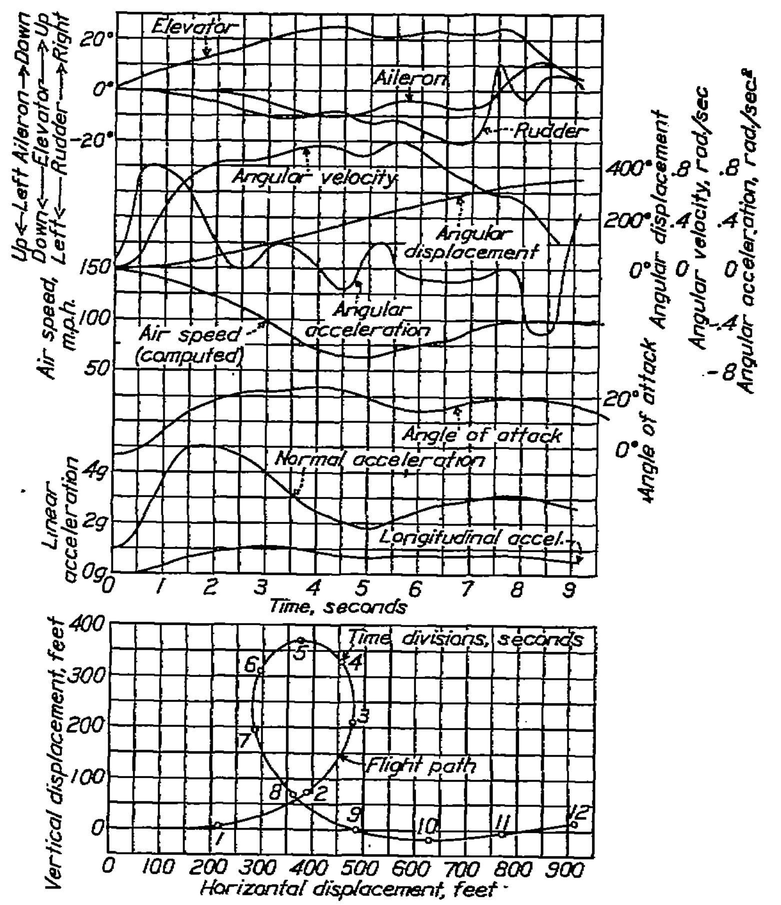

FIGURE 9.—Tight loop

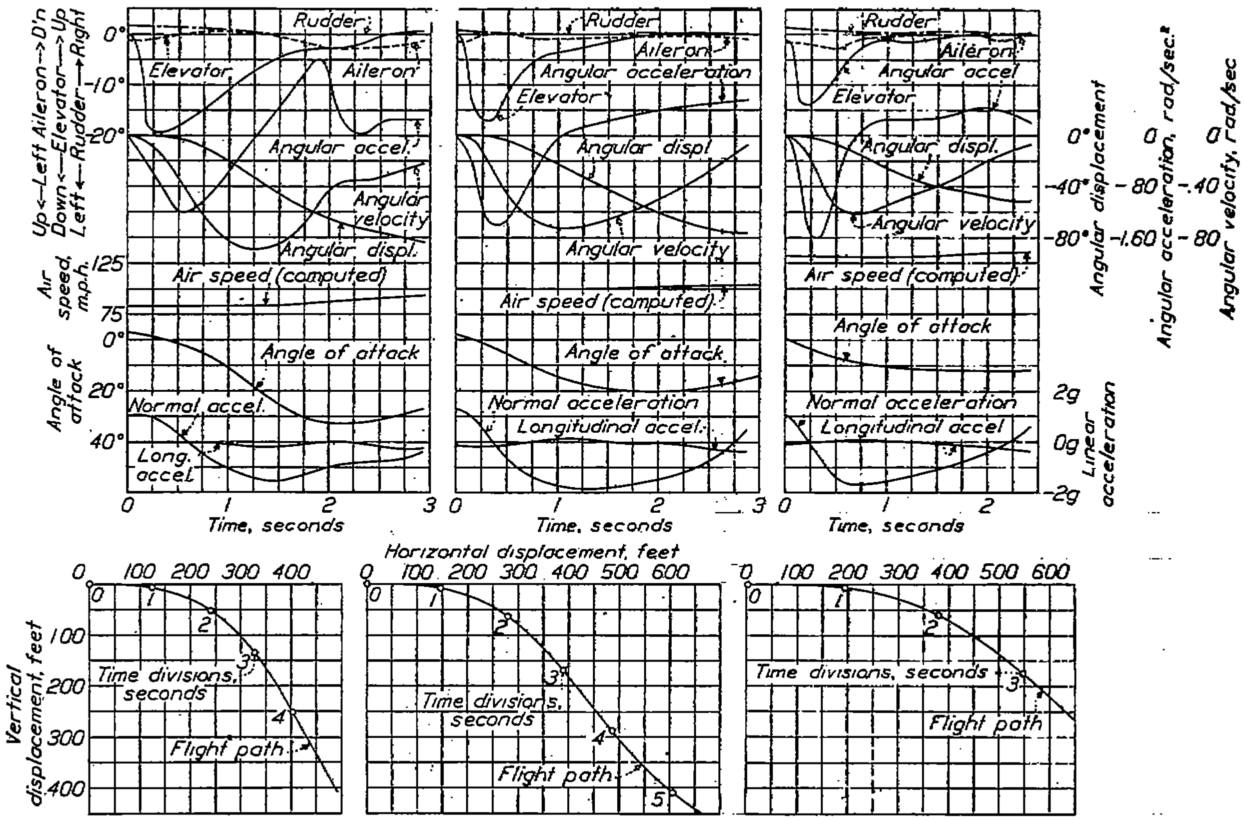

FIGURE 10.—Push-downs

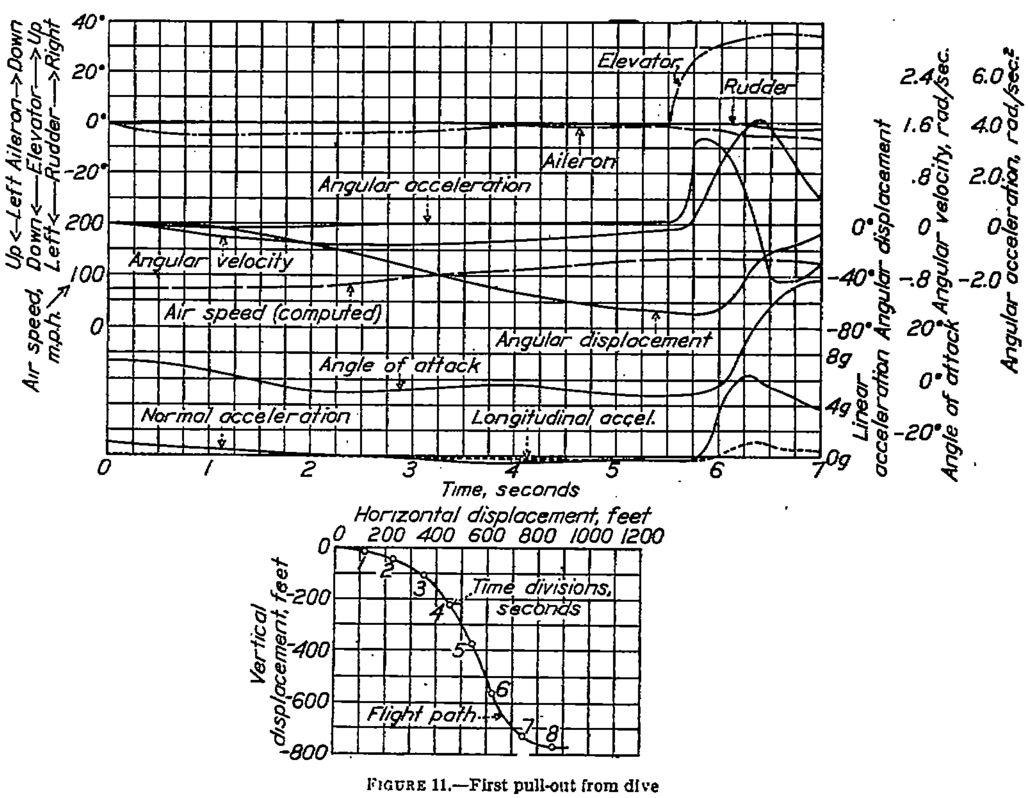

FIGURE 11.—First pull-out from dive

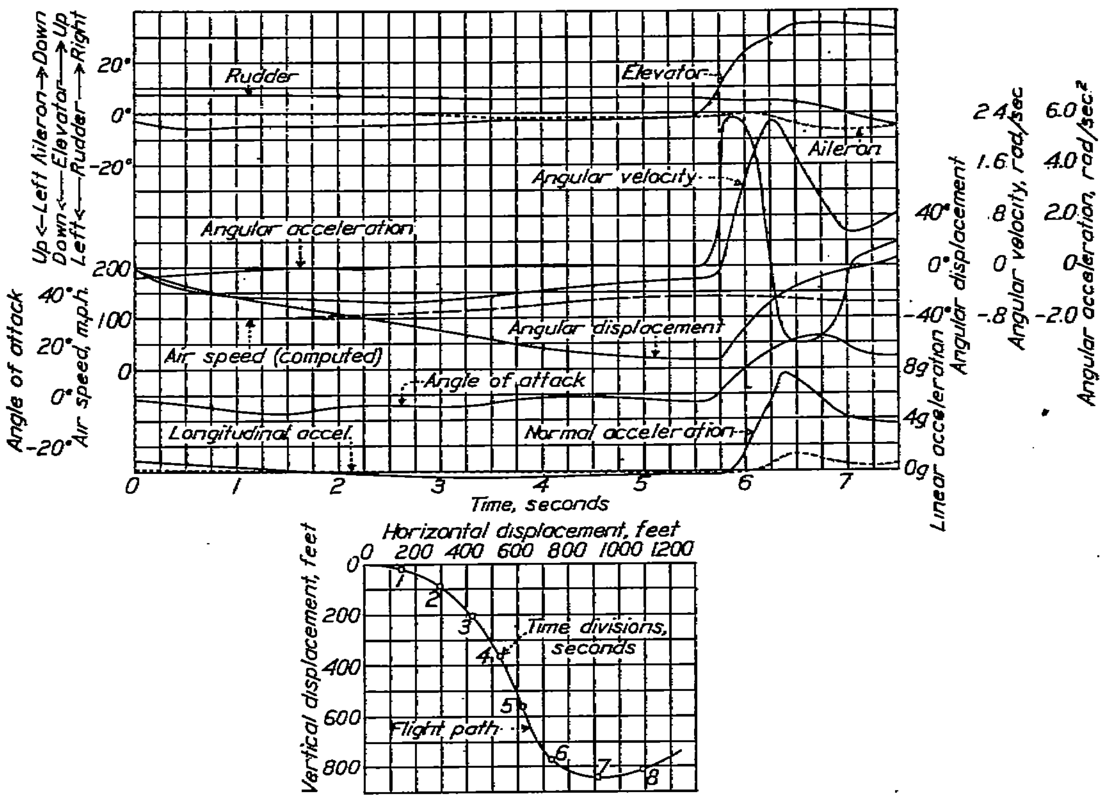

FIGURE 12.—Second pull-out from dive

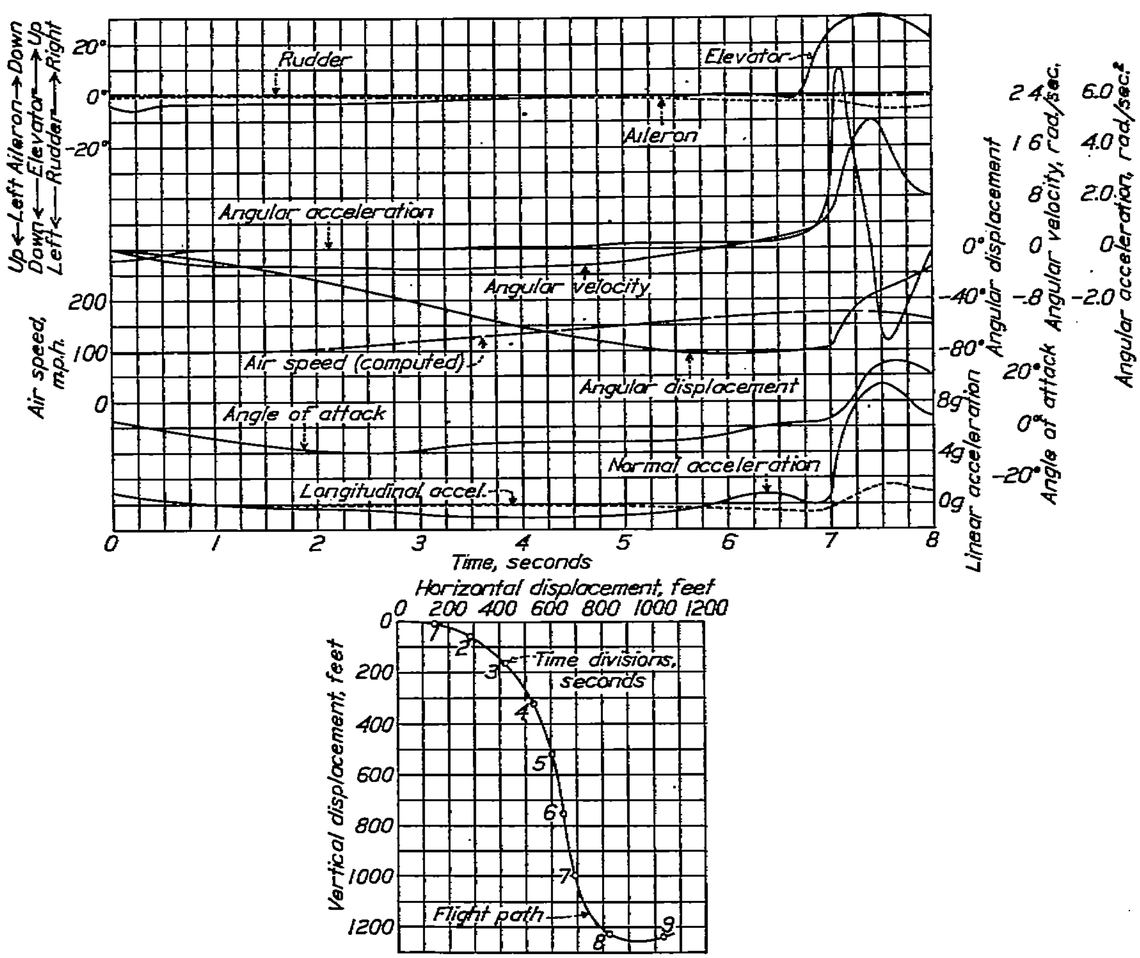

FIGURE 13.—Third pull-out from dive

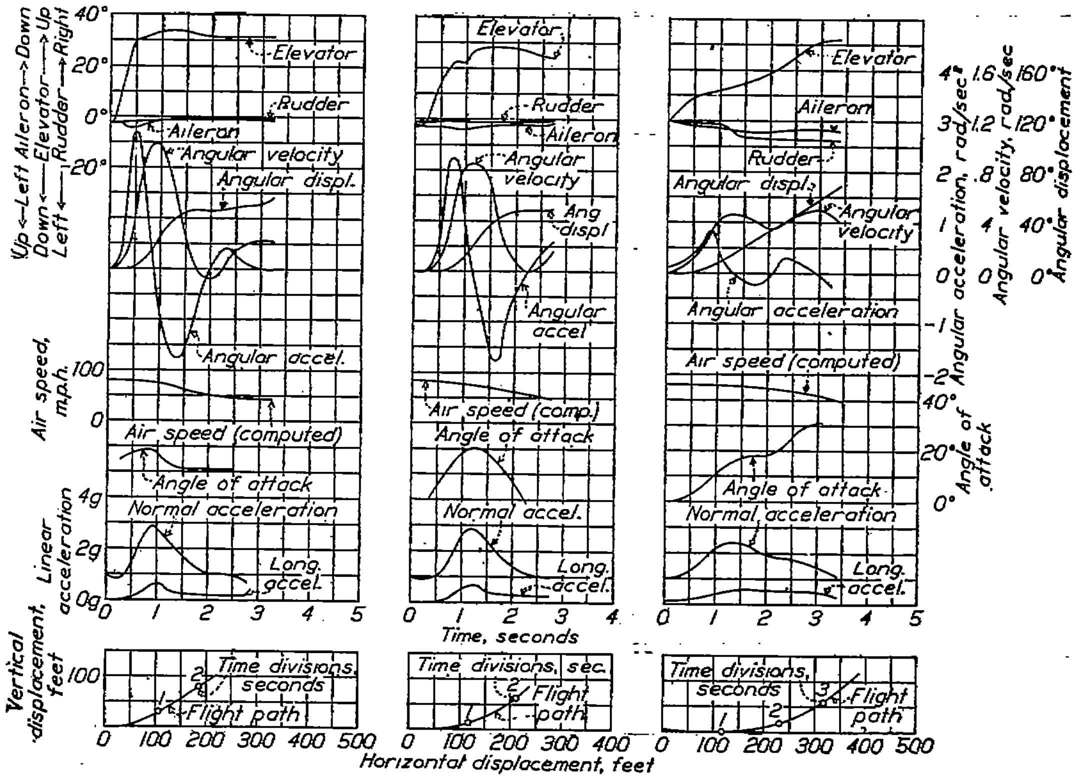

FIGURE 14.—80 m. p. h. pull-up maneuvers, three methods of control

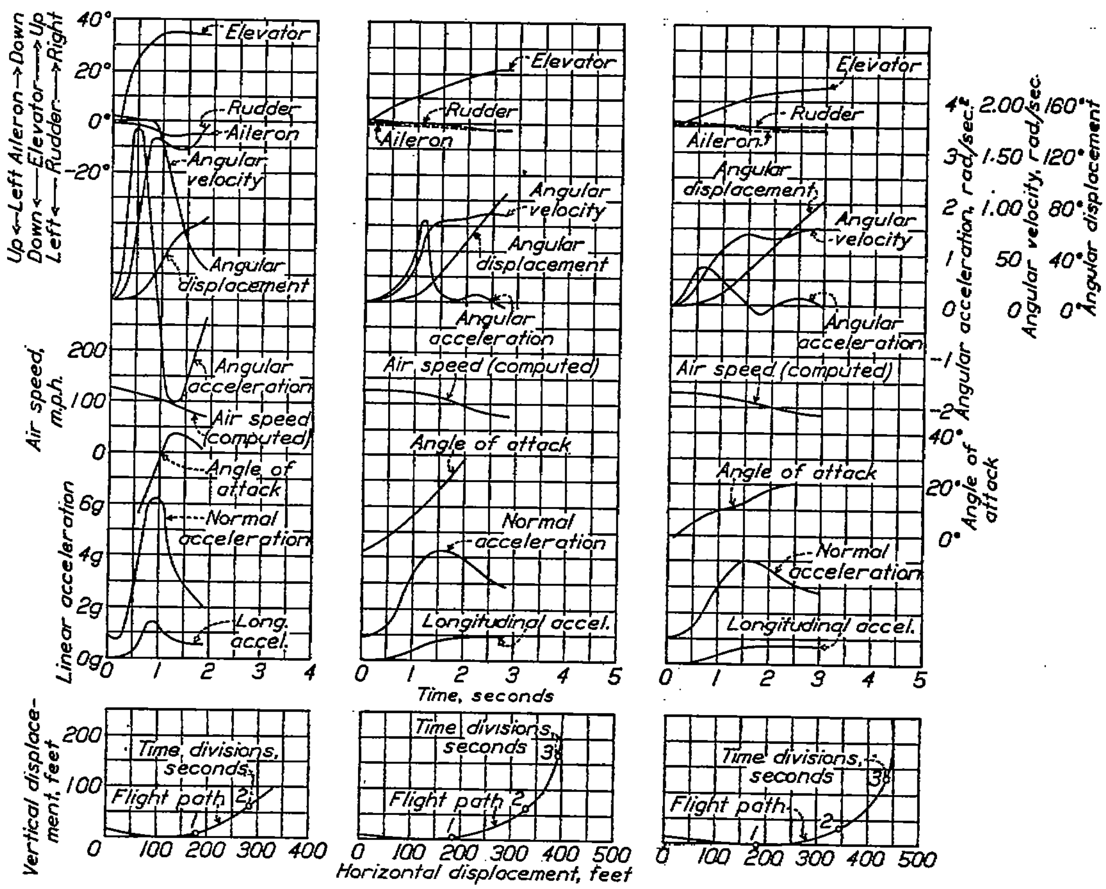

FIGURE 15.—125 m. p. h. pull-up maneuvers, three methods of control

tion of flight and continued to do so until the end of the maneuver. Because of this it was necessary to apply a correction to the flight path and the computed air speed in order to approximate actual conditions. The outstanding characteristics of this turn are indicated in the following table:

Gain in altitude to start of half loop (ft.)	95
Loss in altitude during the half loop (ft.)	465
Horizontal distance required to make turn (ft.)	1, 035
Air speed at start (m. p. h.)	148
Minimum air speed (m. p. h.)	113
Air speed at end of turn (m. p. h.)	160
Time to reverse direction (sec.)	9
Maximum normal acceleration during roll (g)	2. 5
Maximum normal acceleration during half loop (g)	5. 2
Maximum longitudinal acceleration (g)	0. 6
Maximum transverse acceleration (g)	—. 3
Maximum roll angular velocity (rad./sec.)	. 92
Maximum pitch angular velocity (rad./sec.)	. 92
Maximum yaw angular velocity (rad./sec.)	. 16
Maximum elevator displacement (degrees)	10. 5
Maximum down displacement of left aileron (degrees)	11. 5
Maximum up displacement of left aileron (degrees)	6
Maximum rudder displacement to right (degrees)	1
Maximum rudder displacement to left (degrees)	6

This maneuver is sometimes called a reverse turn and frequently an Immelman turn, but wrongly so, because the true Immelman is just the reverse of this maneuver. The Immelman turn is started with a half loop, hence altitude is gained; while in the reverse turn, altitude is lost.

180° vertically banked turns.—Three maneuvers of this type (figs. 20, 21, and 22) were made, and all linear and angular quantities, including velocities and accelerations, were studied in relation to control movement and time. Each maneuver was made to the right with a complete reversal of direction.

All control movements were started at about the same time. The elevator was raised gradually, reaching its maximum displacement about midway in the turn. The rudder and ailerons were moved abruptly at the same time to start a high rolling velocity, and then were gradually decreased to neutral midway in the turn. The roll reached a maximum near the middle of the turn, where the airplane was in a vertically banked position. The maneuver was completed by gradually lowering the

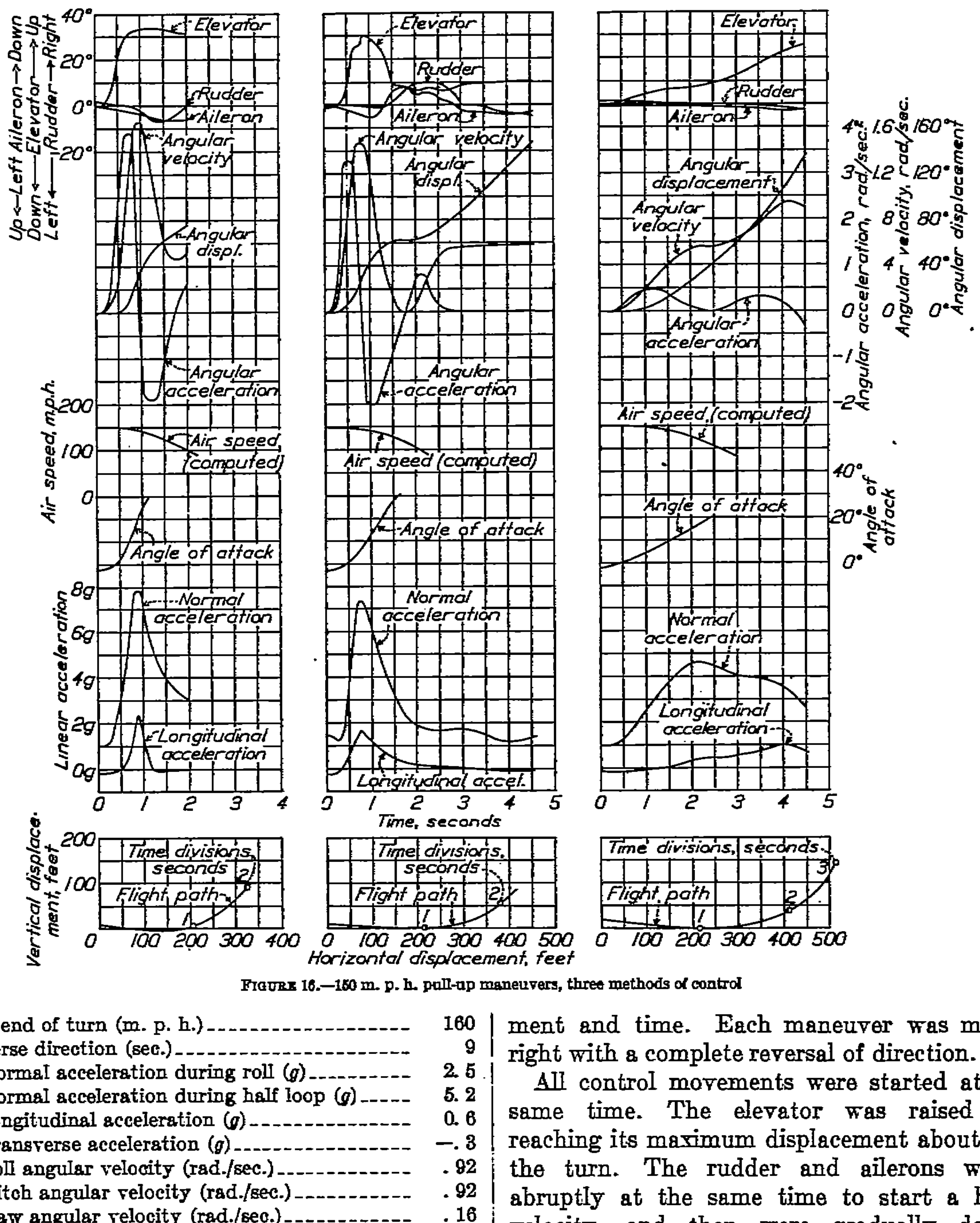

FIGURE 16.—150 m. p. h. pull-up maneuvers, three methods of control

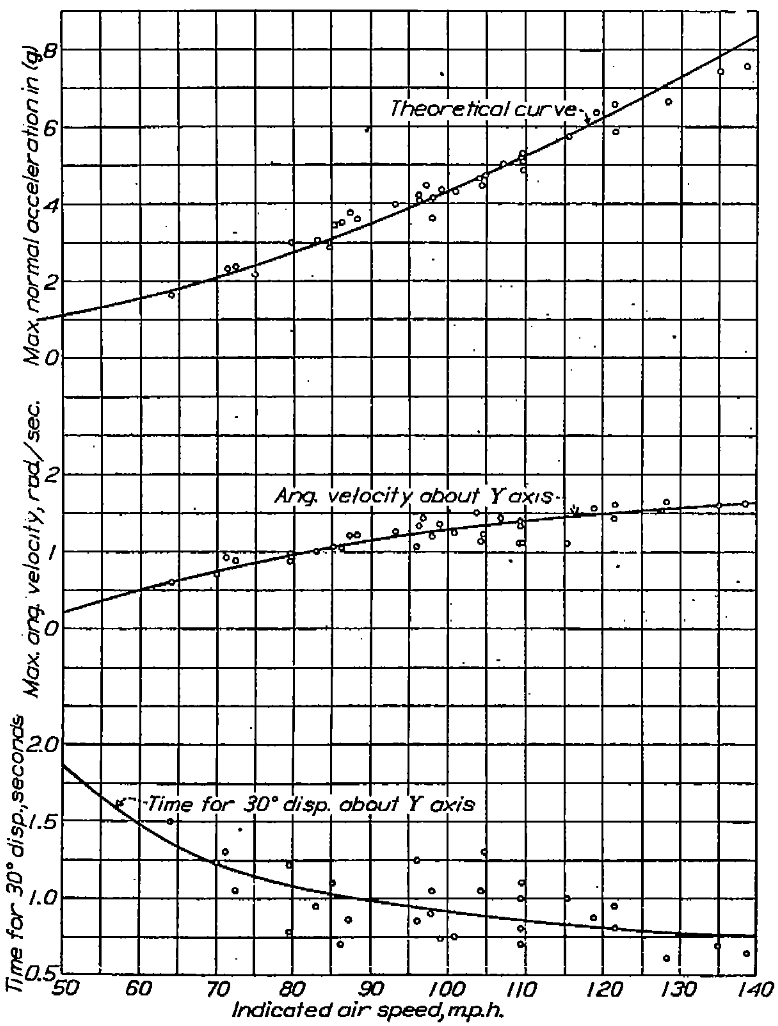

FIGURE 17.—Normal acceleration versus indicated air speed for abrupt pull-ups

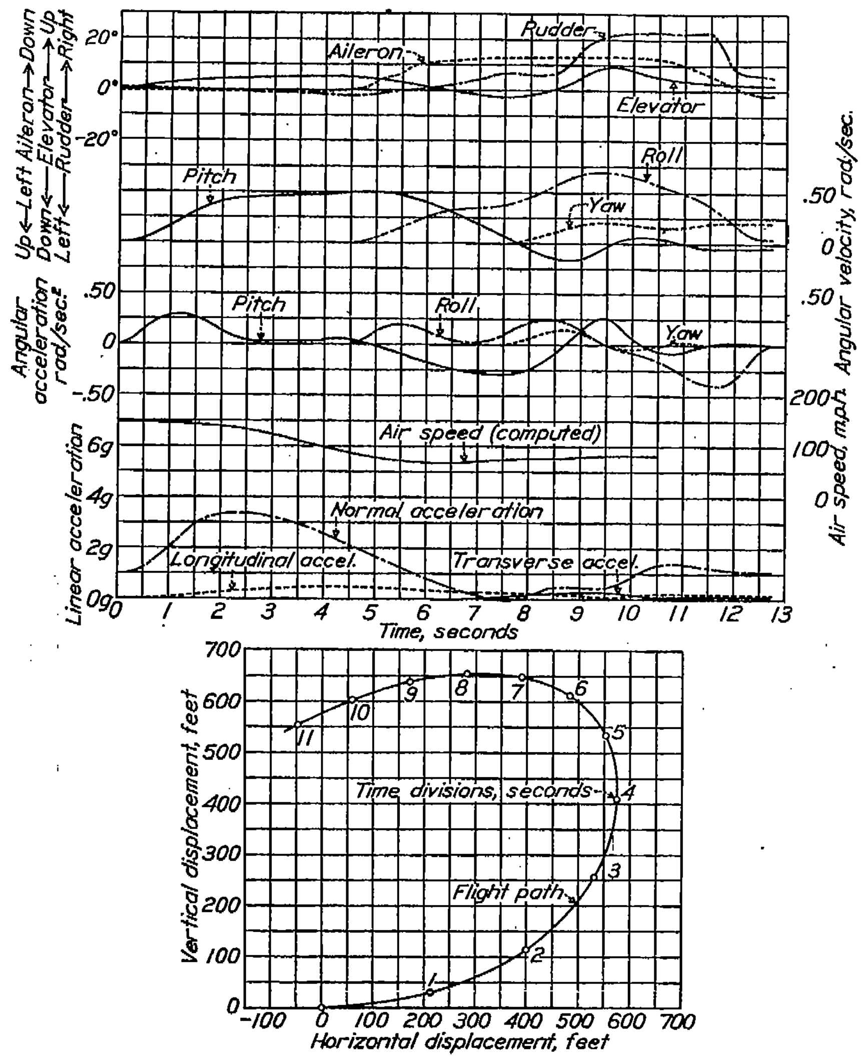

FIGURE 18.—Half loop—half roll

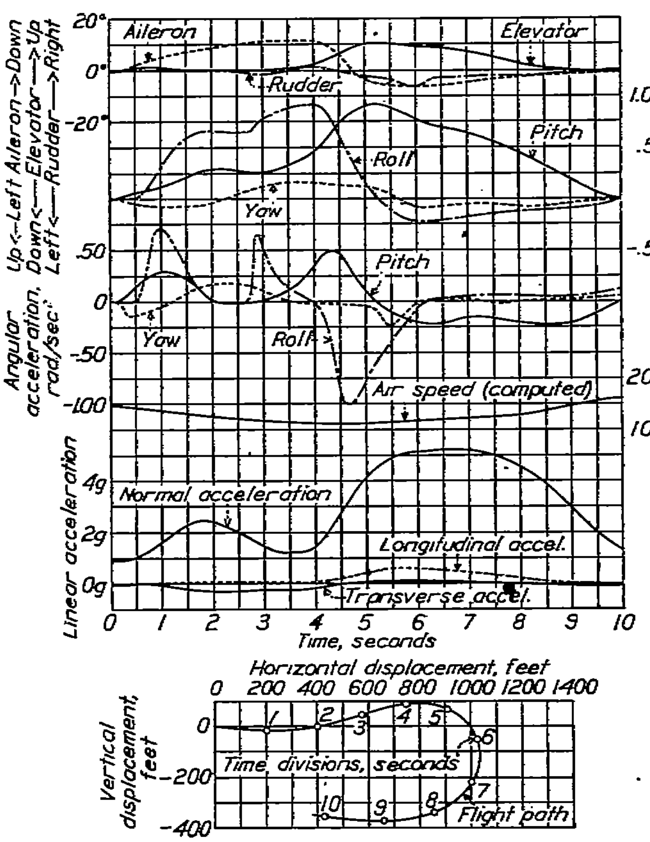

FIGURE 19.—Half roll—half loop

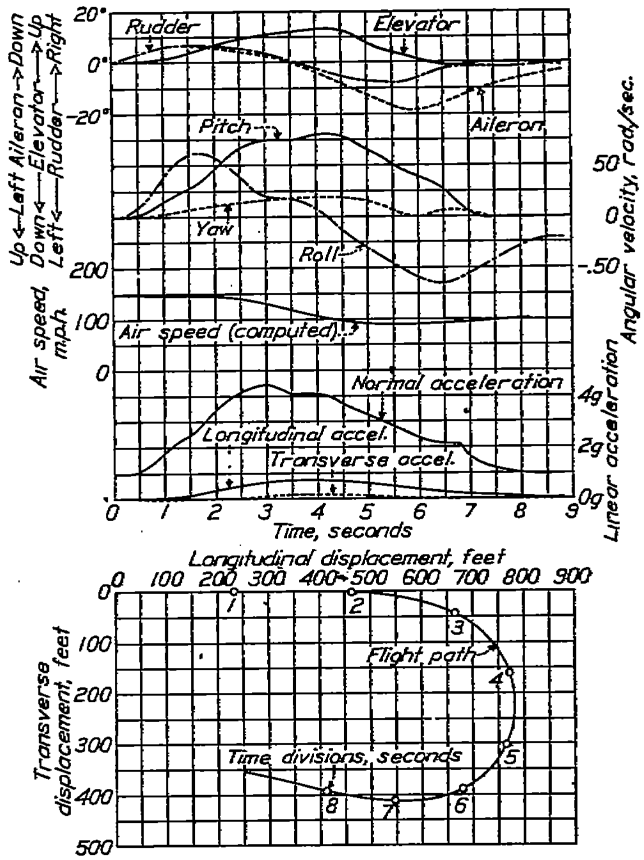

FIGURE 21.—148 m. p. h. vertical bank turn

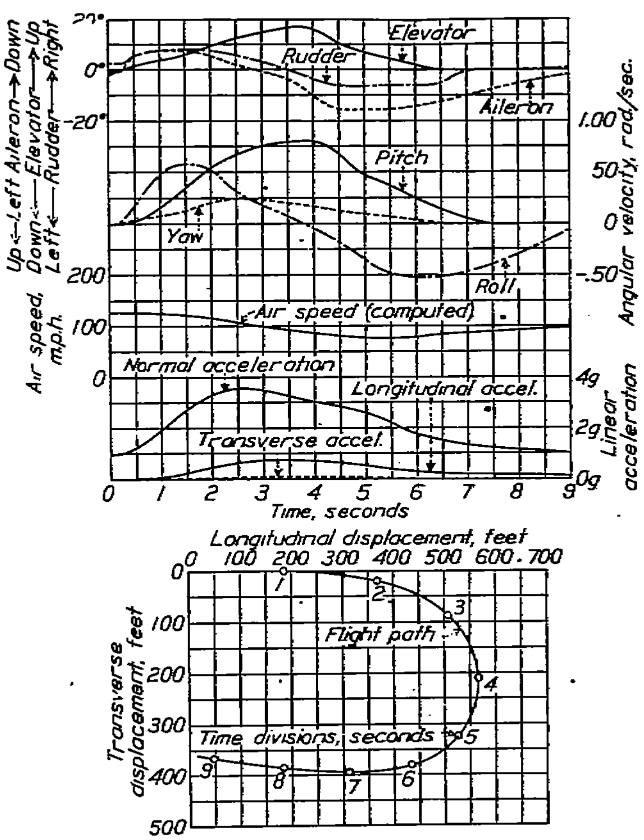

FIGURE 20.—128 m. p. h. vertical bank turn

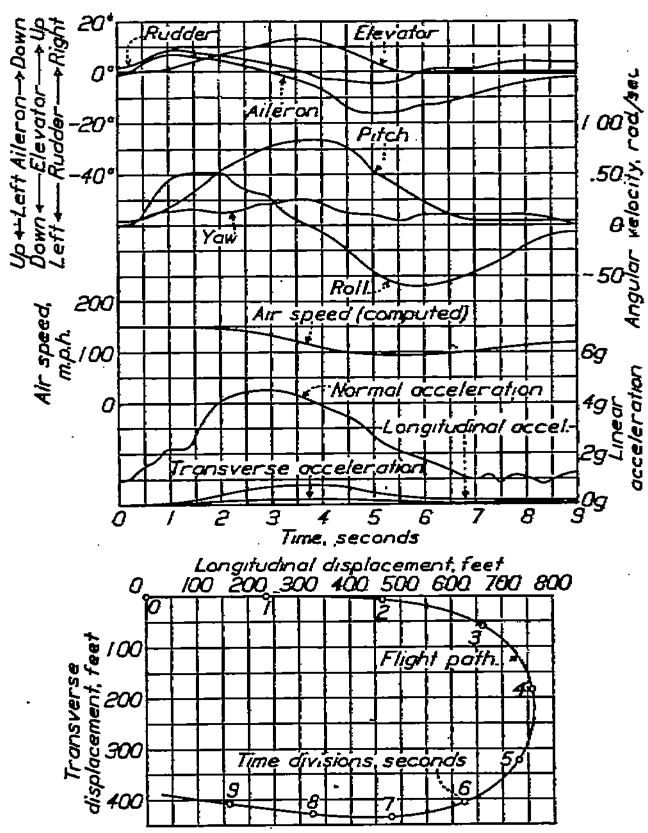

FIGURE 22.—150 m. p. h. vertical bank turn

elevator and applying opposite rudder and aileron control.

All instrument records for the three turns were obtained for a period of approximately nine seconds. The air speeds at the beginning of the maneuvers were 128, 148, and 150 miles per hour, and the time required to complete 180° was approximately seven

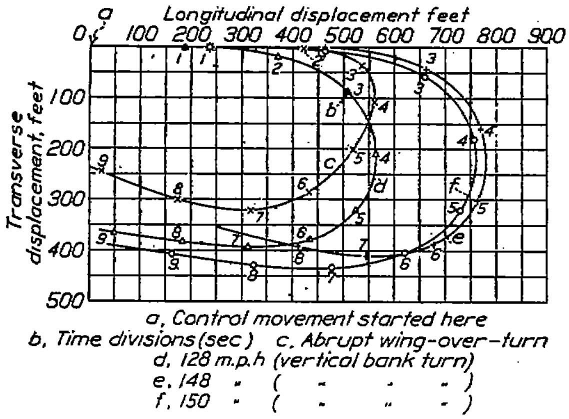

FIGURE 23.—Comparison of flight paths for 180° turns

seconds for each, but showed a tendency to increase slightly with the speed of the maneuver.

The time, which was determined from the flight path, is that required for a complete reversal of direction, but not necessarily that required for return to steady horizontal flight. In fact, the curves of angular velocity show that there is still considerable pitching and rolling at the times indicated for the completion of the maneuvers.

The air speed in the slowest turn decreased from 128 miles per hour to 75 miles per hour in 5.5 seconds. At the end of 7 seconds the air speeds for the other two turns had dropped from 148 miles per hour to 90 miles per hour and from 150 miles per hour to 93 miles per hour. With an air speed of 128 miles per hour at the start, the maximum longitudinal displacement was 565 feet. The speeds for the other two maneuvers were nearly alike, so that their maximum longitudinal displacements were very nearly the same, 780 feet for the slower and 760 feet for the higher speed maneuver. The transverse displacements were approximately 400 feet for each turn.

These turns are assembled for comparison in Figure 23 and the principal characteristics are shown in the next table.

Abrupt wing-over-turn.—This turn (fig. 24) was made to the right while descending. It was started by moving the elevator up, the rudder to the right, and the left aileron down. This caused the airplane to nose up slightly, turn and roll to the right, then, when 90° of roll was approached, the right rudder caused the airplane to nose down, and the up elevator caused it to turn further to the right. From this point the aileron and rudder were brought to neutral when the airplane reached an inverted position. The elevator was still up so that the airplane continued to nose downward. At this point the left aileron was moved up and the rudder left, causing the airplane to level out and assume normal flight.

The air speed at the start of the turn was 143 miles per hour and the lowest speed 80 miles per hour. The flight path shows that approximately 180° of the turn had been completed in 6 seconds, but that the airplane had not reached steady horizontal flight at this time. The maximum normal acceleration was recorded during the pull-up at the start of the maneuver.

This turn was made in a shorter time and on a path of smaller over-all dimensions than any of the vertically banked turns, but with a greater loss in air speed, which was due to the abrupt pull-up and roll at the start of the turn. The flight path of this maneuver is also shown in Figure 23 for comparison with the vertically banked turns, and the maximum and other interesting quantities are shown in the following table:

	Vertically banked turns			Abrupt wing-over-turn
Air speed at start (m. p. h.)	128	148	150	143
Maximum elevator displacement (degrees)	17	18	18	11
Maximum rudder displacement (degrees)	8	7	9	9
Maximum rudder displacement (degrees)	−6	−8	−5	−11
Maximum left aileron displacement down (degrees)	7	7	7	6
Maximum left aileron displacement up (degrees)	−16	−18	−16	−15
Maximum angular velocity, Y axis (rad./sec.)	0.8	0.8	0.82	0.75
Maximum angular velocity, X axis (rad./sec.)	+.57 −.52	+.62 −.65	+.5 −.6	+.37 −.7
Maximum angular velocity, Z axis (rad./sec.)	0.25	0.2	0.25	0.2
Time for 180° displacement, (sec.)	7	7.25	7.5	7
Minimum air speed (m. p. h.)	75	90	93	80
Maximum normal acceleration (g)	3.55	4.45	4.5	4.1
Maximum longitudinal acceleration (g)	0.75	0.75	0.75	0.6
Maximum transverse acceleration (g)	0.1	0.15	0.2	−.15
Maximum horizontal displacement (ft.)	565	780	760	560
Maximum transverse displacement (ft.)	305	415	435	320

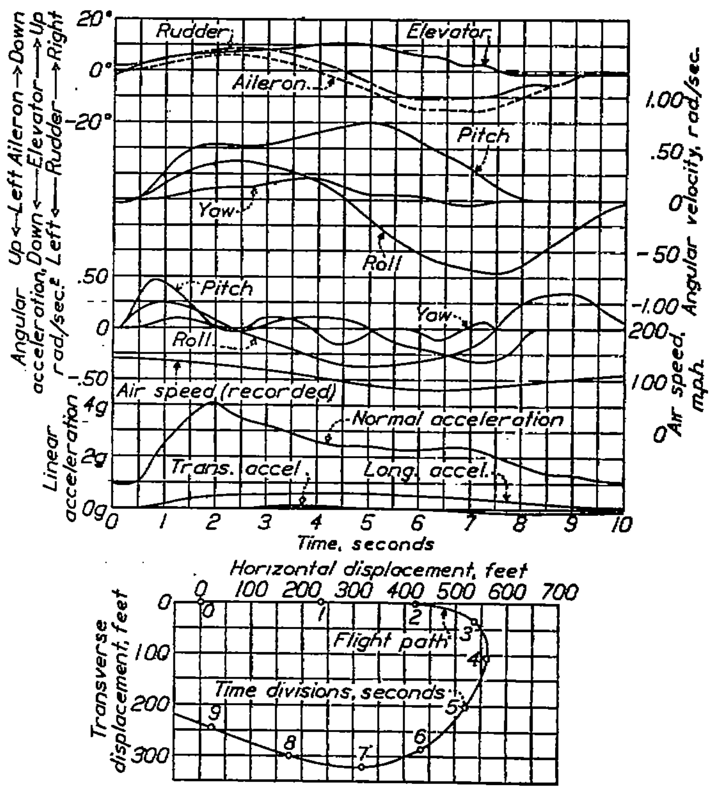

FIGURE 24.—Abrupt wing-over turn

Aileron maneuvers.—A series of right aileron rolls were executed at various air speeds ranging from approximately 75 to 140 miles per hour. In these maneuvers the rudder and elevator were held as nearly as possible in their neutral positions, and the rolls were executed by means of ailerons alone.

All the rolls were started with an abrupt aileron movement and the ailerons held in their position of maximum displacement until approximately 90° of roll had been completed. An aileron movement of about 14° was recorded for the left or down aileron. This indicates a right aileron movement of approximately 28° upward.

A set of representative maneuvers, covering the speed range used, is shown in Figure 25. The angular miles per hour the maximum angular velocity was approximately 0.90 radians per second and the time to 60° displacement was 1.60 seconds. The angular velocities, angular accelerations and times for 60° displacement are plotted versus the respective indicated air speeds in Figure 26.

Rudder maneuvers.—A series of abrupt rudder kicks was made to determine the variations of transverse acceleration, angular velocity, angular acceleration, and the time required for 30° angular displacement with indicated air speed. This information is given in Figures 27 and 28. Although the experimental points for the curve of angular acceleration versus indicated air speed are scattered, this curve does indicate the trend and approximate rate of

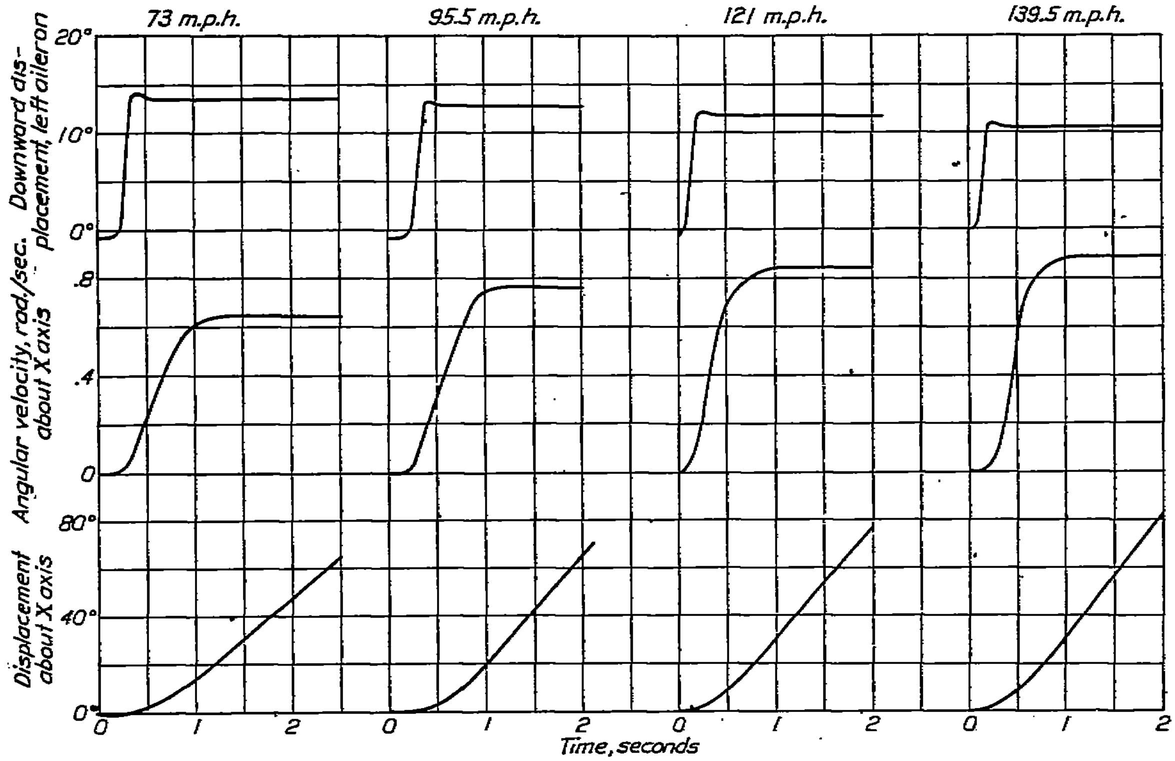

FIGURE 25.—Aileron maneuvers

velocity curves for all the aileron rolls show the same characteristic form. At any air speed with an abrupt control movement, the angular velocity of roll rises rapidly to a maximum value and then is maintained practically constant during the remainder of the maneuver.

The maximum angular velocity attainable rises rapidly with the speed of the maneuver up to about 110 miles per hour indicated air speed. At speeds above this, the angular velocity increases more slowly with an increase in speed. This is due, in part, to the fact that the controls are not displaced so far at the higher speeds.

At an air speed of 75 miles per hour, the maximum angular velocity of roll was 0.65 radians per second and the time to reach 60° displacement of roll was approximately 2 seconds. In a roll executed at 140 increase with speed. The speeds are those recorded at the start of the maneuvers.

Minimum radius of steady horizontal turn.—The minimum radius of horizontal turn was computed for each speed from the angular-velocity recorder records, accelerometer records, and the following equations:

$$R=\frac{a_n}{\omega_r^2} \tag{1}$$

$$V=R\omega_r \tag{2}$$

$$a_n=\sqrt{a_r^2-g^2} \tag{3}$$

R = radius of turn (ft.)

a_n = radial acceleration (ft./sec.²)

ω_r = resultant angular velocity (rad./sec.)

a_r = resultant linear acceleration (ft./sec.²)

Equations (1) and (2) relate to uniform circular motion, while equation (3) removes vectorially the effect of gravity from the resultant linear acceleration.

The individual values of minimum radius are plotted against the respective speeds in Figure 29. The faired curve shows that the minimum radius of turn for sea-level conditions is 135 feet and is obtained at an air speed of 61.5 m. p. h. This may be compared with

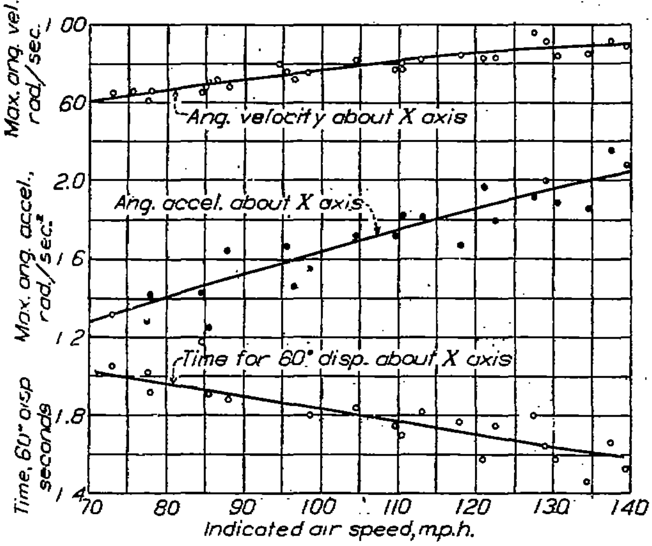

FIGURE 26.—Maximum angular velocity, maximum angular acceleration, and time to 60° displacement versus indicated air speed for abrupt aileron maneuvers.

the minimum radius of 155 feet obtained at 76 m. p. h. with the heavier F6C–3 airplane.

Spins.—Two right spins (figs. 30 and 31), one power-off and one power-on, and two left spins (figs. 32 and 33), one power-off and one power-on, were recorded. In the power-off spins the engine speed was about 570 revolutions per minute, while in the power-on spins

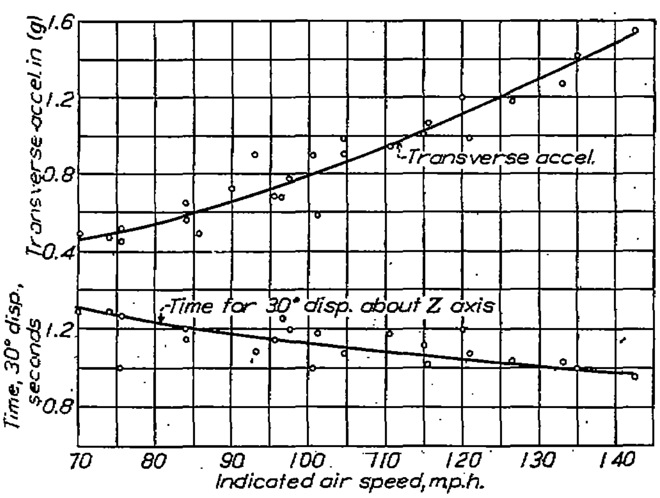

FIGURE 27.—Maximum transverse acceleration and time for 30° displacement versus indicated air speed for abrupt rudder maneuvers

the engine speed was 1,600 revolutions per minute. These maneuvers were started from an air speed near the stalling speed. An inspection of the angular-velocity curves presented in the time histories indicates that none of the spins reached steady conditions, although the right power-on and the left power-off spins approached such conditions toward the end of the records.

Data obtained from the camera-obscura film are presented in the following table with that obtained from the instrument records. The times per turn secured during the latter part of these spins from the angular-velocity recorder records are in agreement with the camera-obscura values within about 10 per cent. The results for the left power-on spin are considerably different from those for the other spins. This is probably due to the gyroscopic couple of the

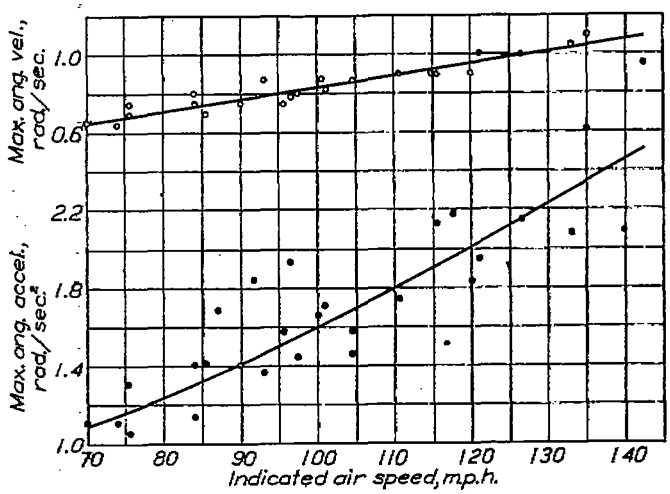

FIGURE 28.—Maximum angular velocity and maximum angular acceleration versus indicated air speed for abrupt rudder maneuvers

propeller. The maximum normal acceleration recorded ranged from 1.80 g for the left power-on spin to 2.30 g for the right power-on spin.

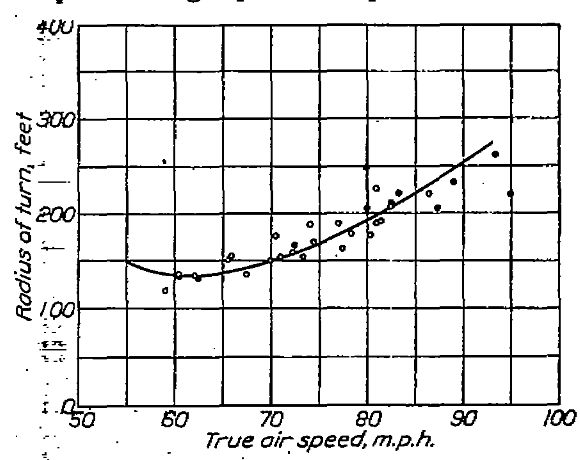

FIGURE 29.—Minimum radius of turn versus true air speed

	Right spins		Left spins	
	Power off	Power on	Power off	Power on
Air speed at start (m. p. h.)	65	62	70	71
Maximum elevator displacement (degrees)	33	33	32	33
Maximum rudder displacement (degrees)	30	29	27	27
Maximum aileron displacement (degrees)		6	11	13
Maximum angular velocity, X axis (rad./sec.)	2.6	2.43	−2.6	−1.95
Maximum angular velocity, Y axis (rad./sec.)	1.55	0.8	1.05	0.98
Maximum angular velocity, Z axis (rad./sec.)	2.48	2.35	−2.12	−1.7
Resultant angular velocity (rad./sec.)	3.78	3.35	3.4	2.7
Resultant angular acceleration (rad./sec.²)	1.15	1.65	−1.85	2.05
Maximum normal acceleration (g)	2.1	2.3	1.95	1.8
Maximum longitudinal acceleration (g)	0.45	0.75	0.35	0.65
Maximum transverse acceleration (g)	−.2	−.15	.15	.10
Time per turn, angular velocity records (sec.)	2.05	2.09	2.23	3.05
Time per turn, C. O. film (sec.)	1.89	1.93	2.20	3.08
Falling velocity (ft./sec.)	91	93	89	105
Diameter of spiral (ft.)	10	10	10	27

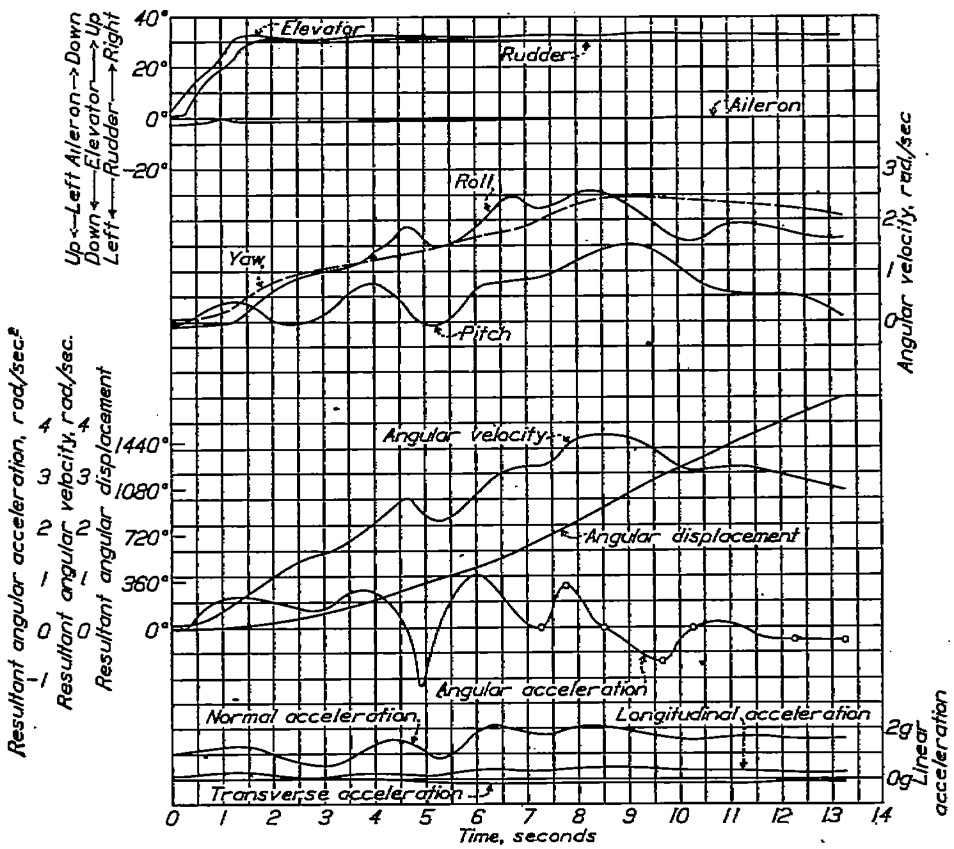

FIGURE 30.—Right spin power-off

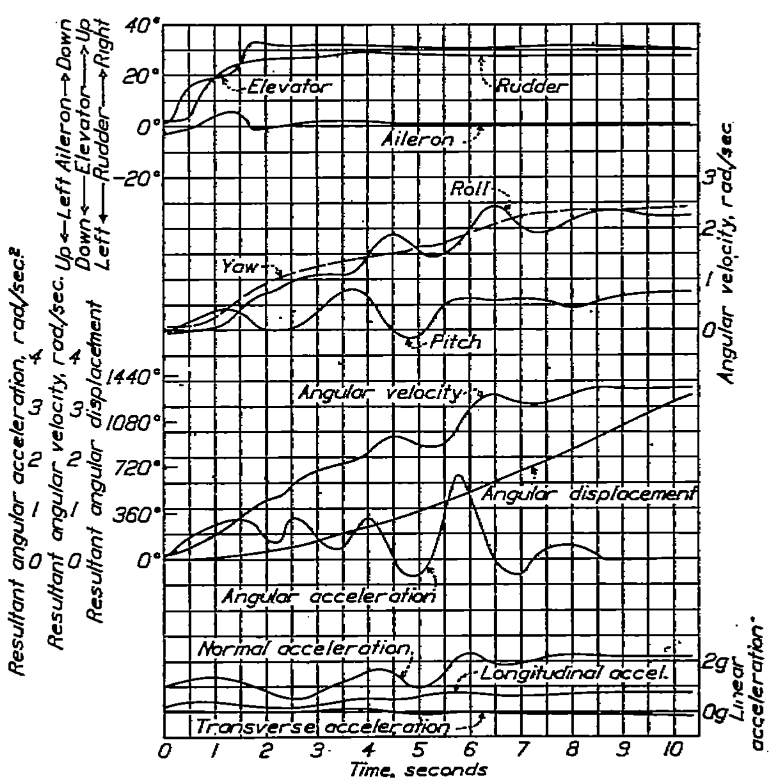

FIGURE 31.—Right spin power-on

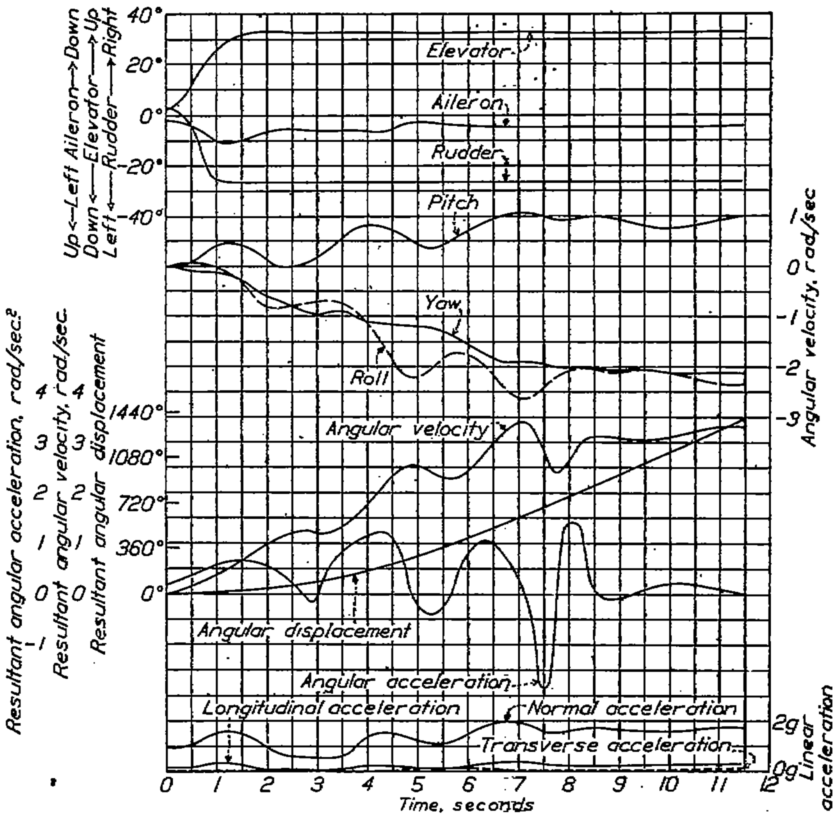

FIGURE 32.—Left spin power-off

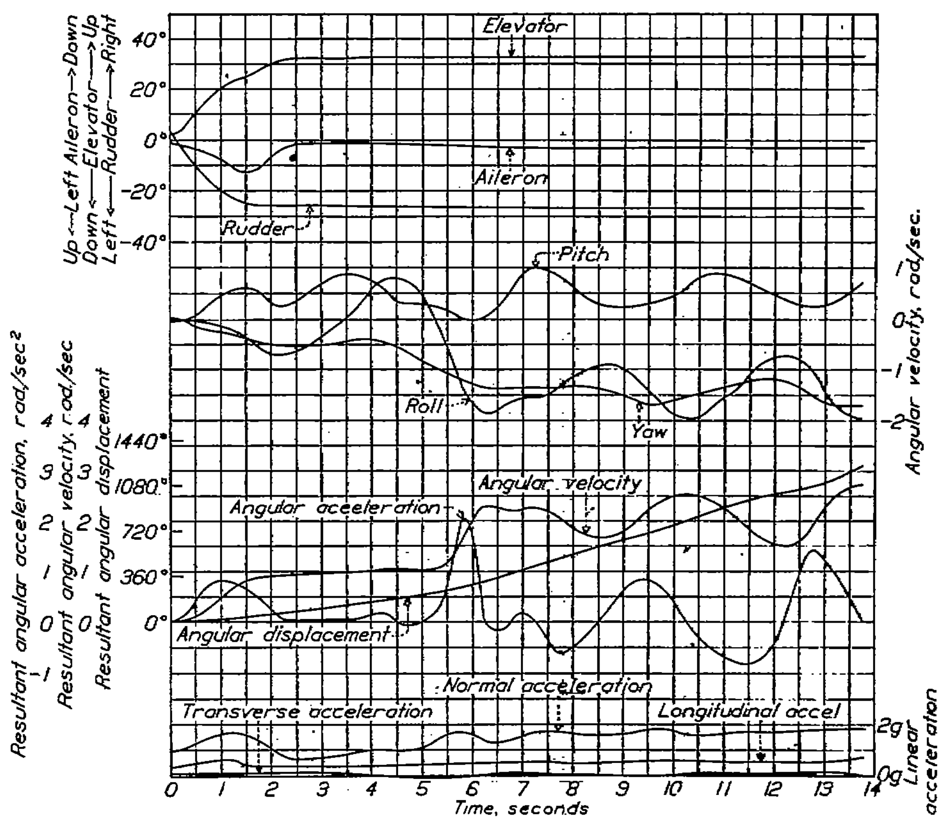

FIGURE 33.—Left spin power-on

Barrel rolls.—One right and one left barrel roll were executed. Both rolls were started at approximately 110 miles per hour. By the end of the maneuvers the speed had been reduced to about one-half this amount. The control movement on the elevator and rudder was similar to that for spins; i. e., an abrupt pull-up rapidly followed by kicking the rudder hard over in the direction of the roll. The ailerons were not used to any great extent. This method of control, as in the spins, caused autorotation which produced a high an axis coinciding with the original line of flight, but is executed on a path making a large angle with the original direction of flight. The sharp break in the line of flight is due to the abrupt rudder kick at the start of the maneuver. As in the spins, the diameter of the spiral path is very small.

SUMMARY OF RESULTS

The principal results of this investigation are summarized in Table I. The times in this table are

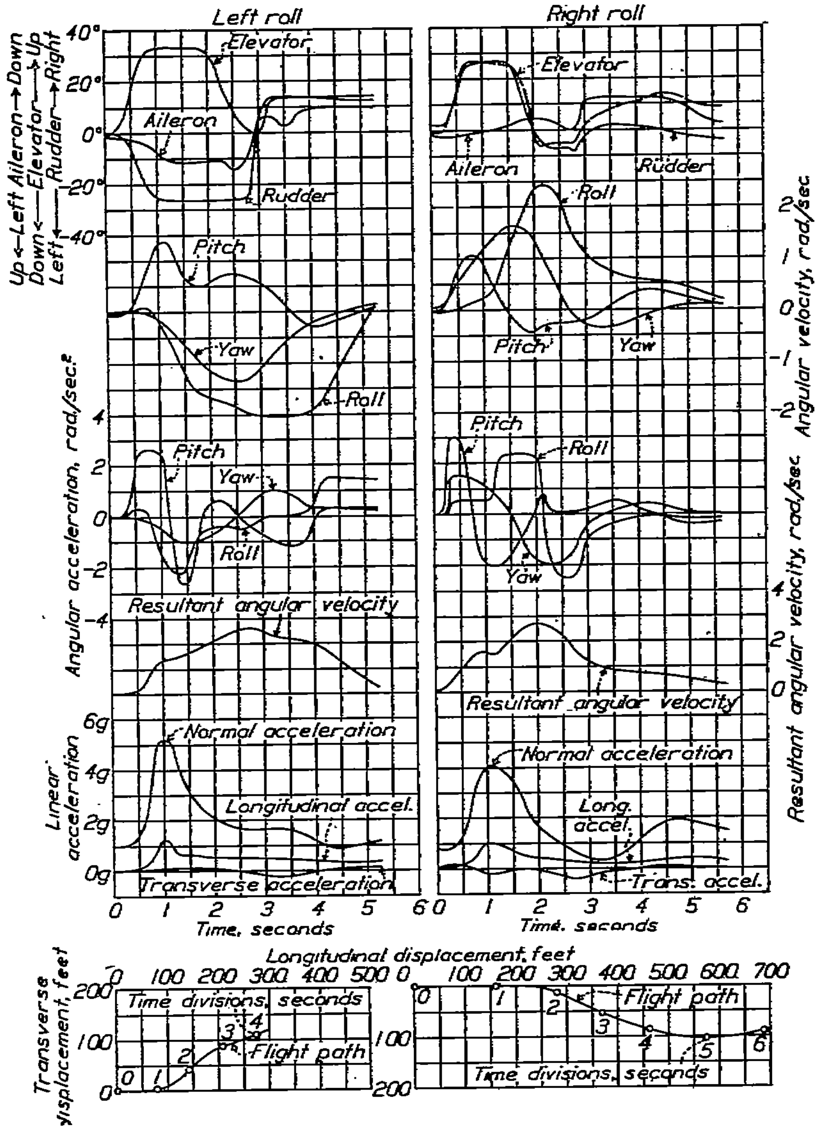

FIGURE 34.—Barrel rolls

rate of angular velocity about the X axis and a yawing velocity from one-third to one-half higher than that obtained from an abrupt rudder kick with the same air speed.

The time histories for these rolls are shown in Figure 34 and the interesting maximum quantities in Table I. Each barrel roll required about 5 seconds for completion. The horizontal projections of these maneuvers are included in the time histories. It may be seen that the roll is not a symmetrical maneuver about measured from the instant the controls are moved from their normal level flight positions. The greatest angular velocity (2.6 radians per second) was found to be about the X axis in a right power-off spin where the resultant angular velocity reached 3.78 radians per second. The maximum normal acceleration recorded was 9.3 g and occurred in a pull-out from dive at 175 miles per hour. It is, of course, impossible to determine from an investigation of this kind the maximum angular velocity and linear acceleration obtainable. It is believed, however, that the above values are the greatest likely to be obtained under service conditions.

Comparison of the loops performed with the F6C–3 and those performed with the F6C–4 shows that the F6C–4 is more maneuverable because a loop made with this airplane was completed in 10 per cent less time than one made with F6C–3, the speed and elevator-control movement being practically the same. The minimum radius of horizontal turn is 135 feet at 61.5 miles per hour for the F6C–4, and that for the F6C–3 is 155 feet at 76 miles per hour. Push-downs made from the same speed with both airplanes indicate that the F6C–3 will increase its speed more rapidly than will the F6C–4. The above conclusions are all in agreement with those to be expected from airplanes differing only in weight and drag.

Even though it is not possible at the present time to state just what maneuvers completely determine the maneuverability of an airplane, it seems that turns of minimum radius, maneuvers giving a complete reversal of direction, and only the abrupt single-control maneuvers, are the most suitable. The abrupt single-control maneuvers are helpful because they are easiest to duplicate. It is probable, however, that some maneuver involving the use of all controls could be utilized to completely measure maneuverability.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *December 12, 1930.*

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APPENDIX

SPECIFICATIONS OF F6C-4 AIRPLANE

Type	Tractor biplane, landplane.
Engine	Pratt and Whitney, R-1300.
Horsepower	425 at 1,900 r. p. m.
Full load	2,582 lb.
Dead load	1,832 lb.
Useful load	750 lb.
Weight per square foot	10.25 lb.
Weight per horsepower	6.1 lb.
Maximum speed	162 m. p. h.
Service ceiling	22,900 ft.
Wing area including ailerons	252 sq. ft.
Aileron area	13.32 sq. ft.
Stabilizer area	18.13 sq. ft.
Elevator area	14.78 sq. ft.
Fin area	4.67 sq. ft.
Rudder area	10.8 sq. ft.
Airfoil section	Clark Y.
Wing span	Upper 31 ft. 6 in., lower 26 ft.
Length	22 ft. 6 in.
Height	9 ft. 3 in.
Gap	4 ft. 5 5/16 in.
Angle of incidence	−2°.
Stagger	38.5 in.
Dihedral	Upper 0, lower 1.5°.
Sweepback	0.

Distance forward from leading edge lower wing to *C. G.*, 6.5 in.
Distance from leading edge lower wing to rudder hinge, 13.5 ft.

TABLE I

	Normal loop	Tight loop	Push-down 85 m. p. h.	Push-down 100 m. p. h.	Push-down 130 m. p. h.	Pull-up from dive 180 m. p. h.	Pull-up from dive 140 m. p. h.	Pull-up from dive 175 m. p. h.	Pull-up from horizontal flight	Pull-up from horizontal flight	Pull-up from horizontal flight	Right spin power-on	Right spin power-off	Left spin power-off	Left spin power-on	Right barrel roll	Left barrel roll
True air speed at start of maneuver (m. p. h.)	148	148	83	100	133	130	140	175	80	127	150	51.5	55	63	64	110	114
Maximum longitudinal acceleration (*g*)	.75	1.1	−.3	−.35	−.35	1.2	1.33	1.5	.6	1.4	2.3	.75	.45	.75	.65	1	1.2
Time (seconds)	9	3	2.85	2.9	2.4	.87	1	.9	1	.8	.72	5.75	8.5	5.75	13.75	.8	1
Maximum transverse acceleration (*g*)												−.15	−.2	−.15	.1	.4	−.3
Time (seconds)												10	6	10	2	2.55	3.25
Maximum normal acceleration (*g*)	4	5	−1.55	−1.85	−1.65	6.4	7.6	9.3	2.9	6.2	7.8	2.3	2	2.3	1.8	4.05	5.15
Time (seconds)	9.75	1.75	1.5	1.4	.8	.8	.87	.82	.9	.82	.72	6	6.25	6	9.75	.85	1
Maximum angular velocity, *X* axis (rad./sec.)												2.43	2.6	2.43	−1.95	2.42	−2.05
Time (seconds)												6.5	8.25	6.5	10.25	1.95	3.1
Maximum angular velocity, *Y* axis (rad./sec.)	.8	1.0	−.89	−.73	−.61	1.64	2.28	2	.99	1.58	1.66	.8	1.55	.8	.98	1.05	1.38
Time (seconds)	7	5.5	1.3	1.15	.8	.87	.75	.75	.9	.75	.80	3.75	9	3.75	7.25	.55	1.1
Maximum angular velocity, *Z* axis (rad./sec.)												2.35	2.48	2.35	−1.7	1.65	−1.82
Time (seconds)												8	9	8	9.5	.35	2.5
Maximum angular acceleration, *X* axis (rad./sec.^{2})																2.3	−2.2
Time (seconds)																1.4	1.25
Maximum angular acceleration, *Y* axis (rad./sec.^{2})	−.44	.8	−1.2	−1.4	−1.6	3.3	5.8	7	2.7	3.35	3.9					3	2.6
Time (seconds)	10.5	.75	.60	.5	.85	.37	.4	.4	.5	.5	.6					.25	.75
Maximum angular acceleration, *Z* axis (rad./sec.^{2})																−2	−1
Time (seconds)																1	1.25
Maximum resultant angular velocity (rad./sec.)												3.35	3.78	3.4	2.7	2.72	2.5
Time (seconds)												5.75	8.5	7.1	13.75	1.8	2.75
Maximum resultant angular acceleration (rad./sec.^{2})												1.65	−1.15	−1.85	2.05	3	4.75
Time (seconds)												5.75	4.9	7.5	5.85	.15	.75
Time to 30° displacement (seconds)						.80	.55	.75									
Time to 45° displacement (seconds)			1.55	1.7	1.95	1.0	.77	1.2	1.5	1.1	.95						
Time to 60° displacement (seconds)			1.90	2.25													
Time to 360° displacement (seconds)	12	10										2.09				4.2	3.85